A THREE - PHASE AC REGULATOR - FED INDUCTION MOTOR WITH IMPROVED SUPPLY POWER FACTOR

A Thesis Submitted
in Partial Fulfilment of the Requirements
for the Degree of

MASTER OF TECHNOLOGY

By

ASHVINI KUMAR GUPTA

to the

DEPARTMENT OF ELECTRICAL ENGINEERING
INDIAN INSTITUTE OF TECHNOLOGY KANPUR

MARCH, 1986

6/1/86

CERTIFICATE

It is certified that this work 'A THREE-PHASE AC REGULATOR-FED INDUCTION MOTOR WITH IMPROVED SUPPLY POWER FACTOR' by Ashvini Kumar Gupta, has been carried out under our supervision and that this work has not been submitted elsewhere for a degree.

(Dr. S.S. PRABHU)
Professor

(Dr. S.R. DORADLA)
Professor

Department of Electrical Engineering
Indian Institute of Technology
Kanpur, India.

ACKNOWLEDGEMENT

I am very grateful to my guides Dr. S.R. Doradla and Dr. S.S. Prabhu for providing me an invaluable guidance throughout my M.Tech. thesis work. My thanks are due to Mr. Rambahadur and Mr. Tripathi of ACES workshop for their invaluable help in making the power module. I heartedly thank Bagaria, Cyril, Nirmal Datta, Jhalani, Mr. R.S. Shrivastava and other friends who directly or indirectly provided with encouragement and help in this work. I acknowledge the sincere efforts of Mr. Yogendra, Mr. Saxena and Mr. Tiwari for typing, tracing and cyclostyling respectively of this thesis.

ASHVINI KUMAR GUPTA

CONTENTS

List of Figures

ABSTRACT

Phase angle control technique is commonly used in thyristor ac regulator circuits supplying passive and active loads. The supply power factor deteriorates as the phase angle increases to decrease the output voltage. This thesis is concerned with the study of an alternative control technique and development of the power circuit to improve the supply power factor. In this technique, the output voltage is obtained symmetrical to the peak of the supply voltage. The displacement factor increases considerably over the entire range of the output voltage, and the power factor also increases. The circuit is built, and the control technique is verified experimentally both with an R-L Load and a three-phase induction motor load. There is a good agreement between theoretical and experimental results.

CHAPTER 1

INTRODUCTION

1.1 General

Electrical drive is an indispensable part of modern industry. The essential requirements for an electrical drive are economy, efficiency, wide range of speed control, accuracy of speed, fast response, capability of running in generative mode, and it should also have good braking capability.

AC commutator motors were widely used for wide range of speed control since these can be supplied directly from ac supply system. DC drives are also used in many industrial applications because of their versatile characteristics. The separately excited dc motors can be easily controlled by varying the armature voltage and field current in order to give speeds below and above normal respectively.

Though an induction motor is basically a constant speed machine, the development of the solid state controllers has made the speed control of an induction motor easy. Presently a number of solid state controllers are available for an ac machine depending upon the requirements of a drive. For accurate speed control, closed loop control is a must in any application involving a drive system.

Both induction motor and solid state controller have numerous advantages. Induction motor is rugged, and cheap. It has very high speed limit with no limit of stator voltage, very small mechanical wear and tear, and high power/weight ratio. On the other hand, a dc motor has a number of limitations such as frequent maintenance of brushes due to commutation, low power/weightratio, low voltage limit and so on. Presently induction motors are preferred over dc motors. The solid state controller is compact, highly efficient, and versatile. It has a fast speed of response and long life.

1.2 Solid State Control Techniques

There are different solid state power controllers which can be used for the speed control of induction motors.

1.2.1 V/f Control

Since the speed of an induction motor is approximately proportional to frequency of the supply voltage, the inverter provides a very good speed control over a wide range by variation of the supply frequency keeping the V/f ratio constant for maximum air gap flux. Although this is an expensive method of speed control, but this is preferred for inaccessible locations.

1.2.2 Rotor Resistance Control

Variation of resistance of the rotor circuit provides a wide range of speed control at constant voltage and frequency. This method is used with slipring induction motor. A rectifier-chopper is used to change the effective resistance of the rotor circuit smoothly and steplessly. This method of speed control is commonly used for applications requiring high starting torque as in excavators and cranes. However, This method is inefficient owing to losses in the additional resistance in the rotor circuit.

1.2.3 Rotor Power Control

The speed of an induction motor can be controlled through rotor power control in subsynchronous and supersynchronous speed ranges. For subsynchronous speed range, power is taken from the rotor circuit and fed back to the supply. For supersynchronous speed range, power is fed to the rotor from the supply. In order to obtain speeds in subsynchronous and supersynchronous range as well, two controlled converters are used in the rotor circuit.

1.2.4 Stator Voltage Control

This method is widely used for low power applications because of its economy and simplicity.

Fig. 1.1 shows motor operation with a constant load torque for different voltages.

The torque developed by an induction motor is proportional to the square of the voltage, and the current is proportional to the voltage. Hence at low voltages torque/current ratio is small.

With a constant load torque, the current also increases with slip as

$$T \alpha \frac{I^2R}{S}$$

where R_2 is the rotor resistance

and T is the motor torque.

$$\text{or} \quad I \alpha \sqrt{S/R_L}$$

With a constant rotor resistance this reduces to $I\alpha\sqrt{S}$.

For a constant torque, the speed range of a motor is small even at low load torques. This can be increased by increasing the rotor resistance, but will result in increased copper loss, which in turn necessiatesderating of the motor.

If a motor drives a fan, a blower or a pump load where the torque-speed characteristic is parabolic, then the voltage

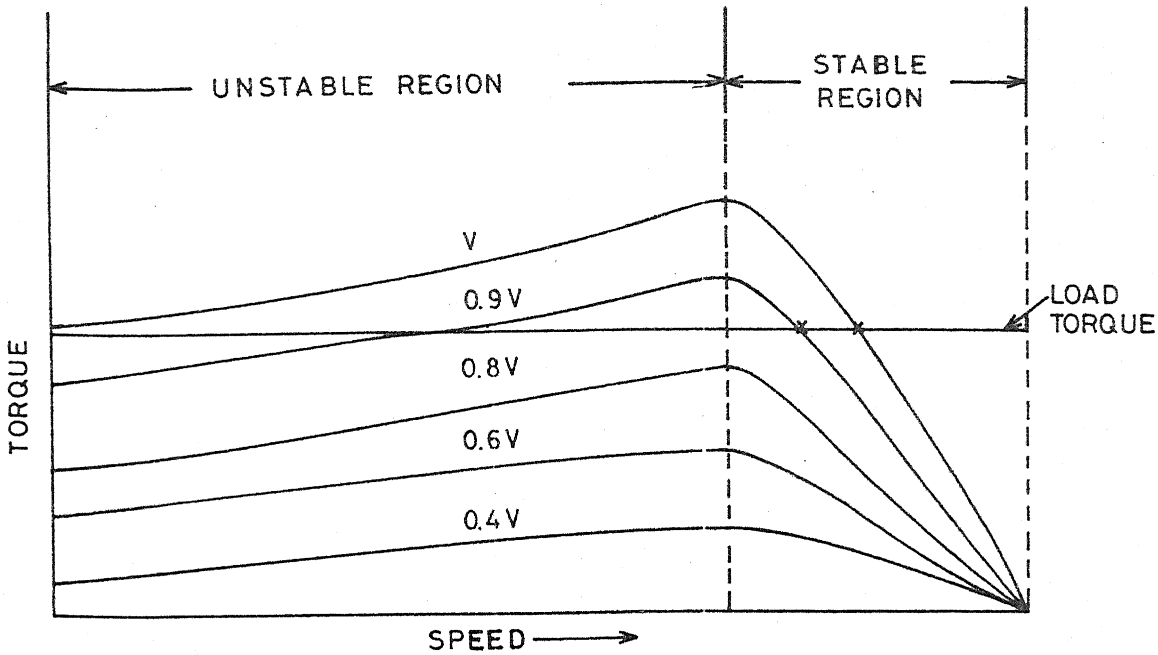


FIG. 1.1 MOTOR OPERATION WITH CONSTANT TORQUE LOAD.

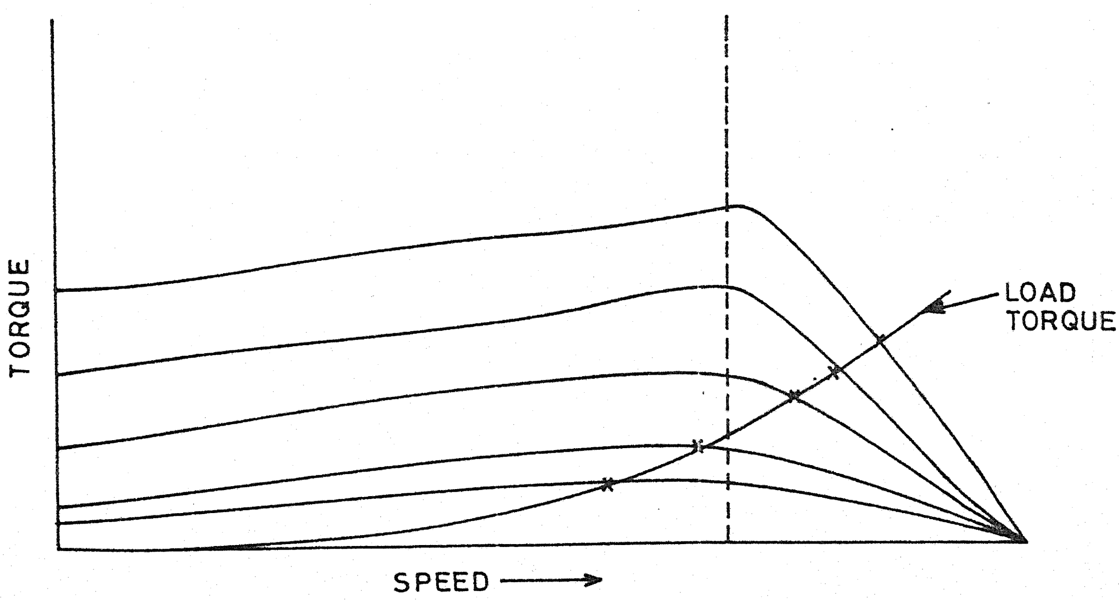


FIG.1.2 MOTOR OPERATION WITH FAN LOAD.

control provides useful speed control.

Fig. 1.2 shows the motor operation with a fan load.

$$T \alpha (1 - S)^2$$

$$\text{and also } T \alpha \frac{I^2 R_2}{S}$$

$$\text{so } I \alpha \frac{\sqrt{S(1 - S)}}{\sqrt{R_2}}$$

In this case the current does not increase with the slip for the full range. The peak current occurs at 33 percent slip. At low speeds, Torque/current ratio is not poor as in the case of a constant load torque. It can be seen that the motor has a wide speed range with such a load, because the motor runs in unstable region also.

Another advantage with such type of loads is, they have a low starting torque and therefore the motor starts at even low voltage and hence the starting current of the motor is not very high.

The voltage fed to the motor can be controlled by giving the supply through a variable resistance, a variable reactance or an auto transformer. These methods are either sluggish or less efficient or both.

The solid state voltage control is obtained by connecting two thyristors back to back connected in each line. The output voltage is controlled by controlling the duration of the conduction in each half cycle. By changing the firing angle, the conduction interval is controlled. This is known as phase angle control technique.

For a three-phase induction motor, there are various ways of connecting the controller.

Fig. 1.3 shows some of the circuits suitable for a three-phase induction motor. A comparative study of these configurations is made in reference [1] .

Some of these circuits provide balanced while others provide unbalanced voltage. However in both cases the voltage fed to the motor is non_sinusoidal. Harmonics currents are produced in the load and the supply lines. It has been concluded that the circuit configuration of Fig. 1.3 (g) results in minimum rms current, from the source.

The phase angle delay control technique is commonly used to vary the output voltage in all these circuits. The main advantage of the phase control techniques is the simplicity of commutation. However it has several disadvantages. The displacement factor decreases as the delay angle is

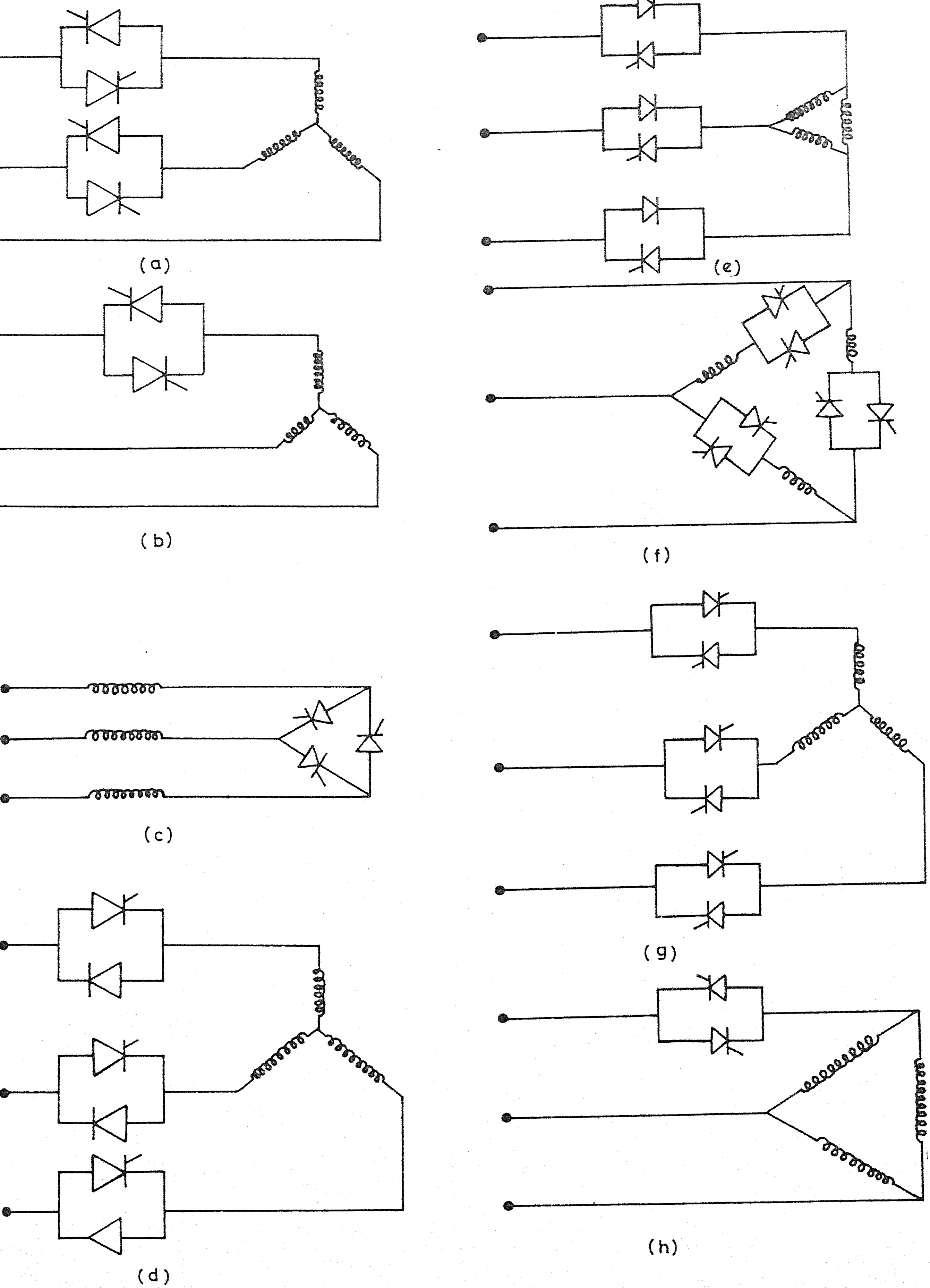


FIG.1.3 SOLID STATE CONTROLLERS FOR THREE PHASE INDUCTION MOTOR.

increased to reduce the output voltage. Also harmonic currents are drawn from the source. Both these factors contribute to poor source power factor. If the harmonic content of the source current is high, the motor may have to be derated. Further, the motor rating is also to be limited if there is a tendency to distort the supply voltage. It is therefore desirable to improve the power factor by alternative control technique. Pulsewidth modulation control techniques have been investigated in the case of ac-dc converters in sufficient detail for improving supply performance and the load performance as well [2].

These techniques can also be applied to thyristorised ac regulators intended for application to fans, pumps and blowers.

PWM control technique has been applied to ac chopper by Mozdzer and Bose [3] to run a three-phase induction motor. Symmetrical voltage ac chopper supplying R.L. load has been studied in the reference [4] which is reported very recently. The power factor is improved considerably with this control technique. The idea of improving the power factor with a symmetrical voltage ac chopper has been conceived independently. This thesis is concerned with the study of a three-phase motor

fed by a symmetrical voltage ac chopper.

The control circuit and power circuit have been built and tested on a laboratory sized three-phase induction motor. There is a good agreement between experimental and analytical results. The chapter-wise contents are given in the next section.

1.3 Outline of Thesis

In chapter 2, possible schemes for ac chopper are discussed. Problems relating to the ac chopper are discussed in detail. The design of the control scheme for the chopper is also included in this chapter.

In chapter 3, the steady state harmonic equivalent circuits are discussed for determining the steady state performance both in the source and the load employing the symmetrical voltage chopper. The simulation results relating to the steady state performance are given in chapter 4. Experimental results validating the simulation results also included. Oscillograms of typical waveforms of voltage and current are also included in this chapter.

Conclusions and scope for future work are given in chapter 5.

CHAPTER 2

DESIGN AND FABRICATION OF SYMMETRICAL VOLTAGE CHOPPER

2.1 Introduction

In the symmetrical voltage chopper the source is connected to the load at α, and disconnected from the load at $(\pi - \alpha)$ in each half cycle of the supply voltage. The voltage pulse delivered to the load is thus symmetrical to the peak value. If the load current is inductive then a large voltage is induced. To avoid such voltage spikes, an alternative path is to be provided for the load current. In the ac to dc converter a diode is connected in parallel with the load to allow the current to freewheel whenever the source current is interrupted. But with ac loads, a diode can not be connected across the load circuit since the load voltage is alternating in nature. An alternative power circuit is required for implementing symmetrical voltage chopper.

2.2 Development of Chopper

Fig. 2.1 shows a circuit which is used for the symmetrical voltage control. When the switch S_1 is on and S_2 is off then the source feeds power to the load, and when S_1 is

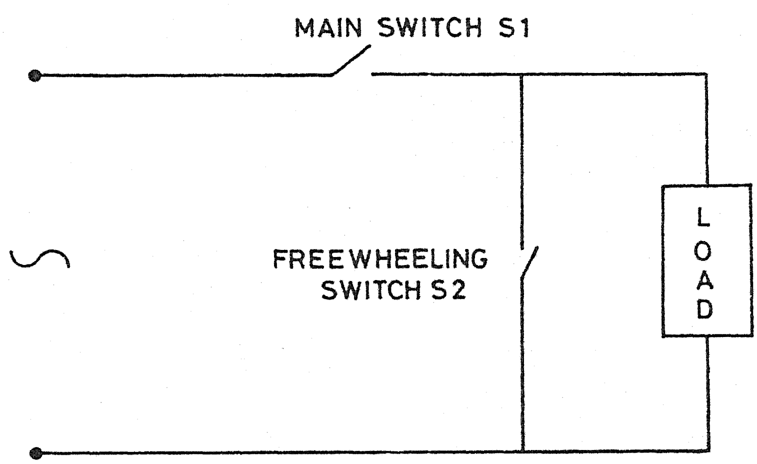


FIG. 2.1 SYMMETRICAL VOLTAGE CHOPPER.

off and S_2 is on then the load is cut off from the source and the current in the load freewheels through the switch S_2, and the output voltage is made zero. This circuit can be realized by either thyristors or transistors.

Fig. 2.2 shows the circuit realized by thyristors. Each thyristor block contains a thyristor and its commutation circuitry. Fig. 2.3 shows the load voltage and current waveforms. At the angle α in the positive half cycle, the source is connected to the load and the current at this instant being negative, the thyristor T_2 is turned on. After the current becomes zero at θ, the thyristor T_1 is turned on. At angle $\pi-\alpha$ the thyristor T_1 is turned off in order to obtain output voltage symmetrical to the peak value. At the same instant the thyristor T_1' is turned on to provide a freewheeling path to the load current.

This circuit requires a commutation circuitry for each thyristor, and the complete circuit becomes complex and uneconomical. To reduce the complexity and to make the circuit economical the thyristors can be replaced by transistors. The transistors do not require commutation circuit since the transistor can be turned off by blocking the base current. Fig. 2.4 shows the chopper with transistors. The working of the circuit is similar to the circuit of Fig. 2.2. NPN transistors (MJ 10009) are used. This transistor is an integrated circuit

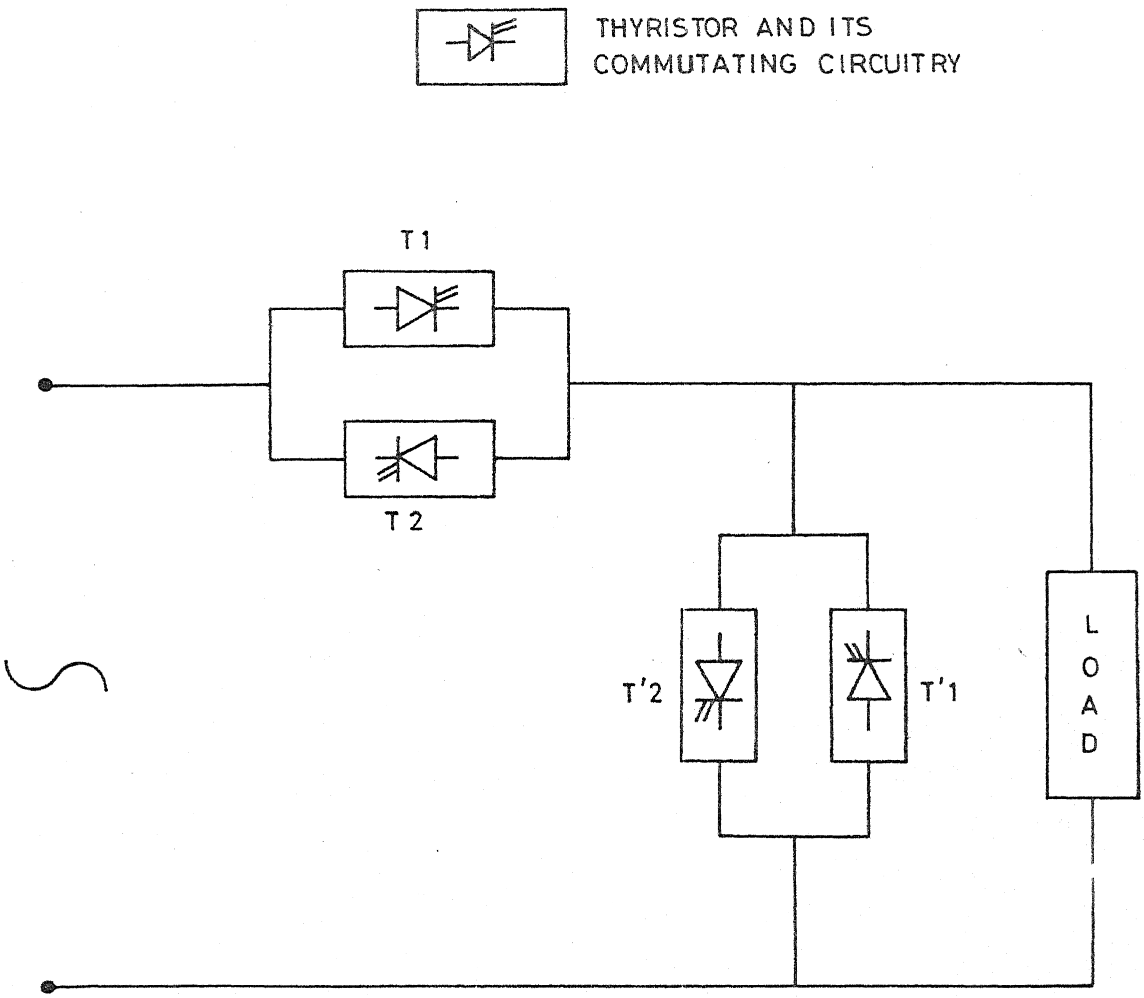


FIG. 2.2 THYRISTORISED SYMMETRICAL VOLTAGE CHOPPER.

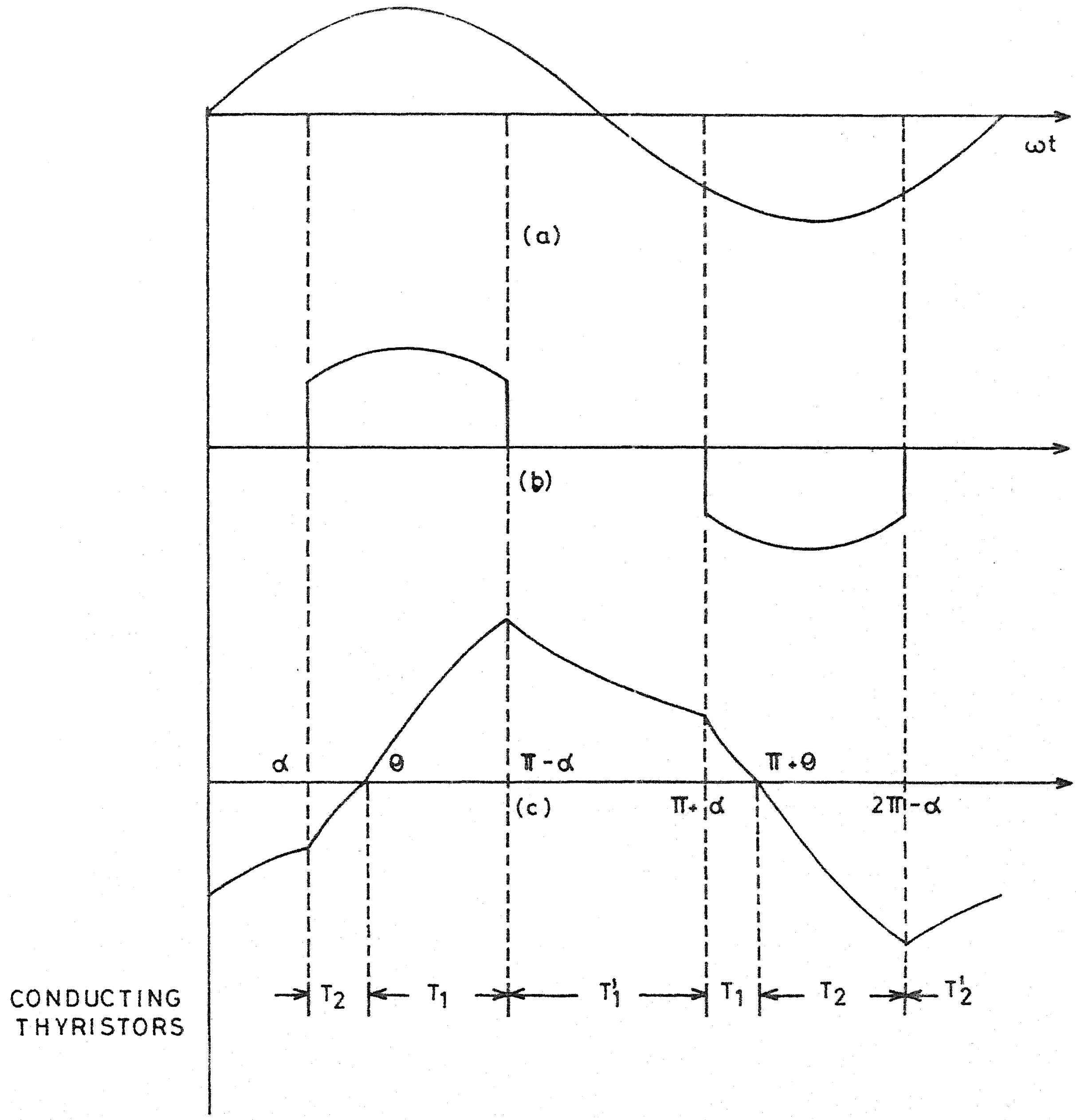


FIG. 2.3 WAVE FORMS

(a) INPUT VOLTAGE

(b) OUTPUT VOLTAGE

(c) LOAD CURRENT

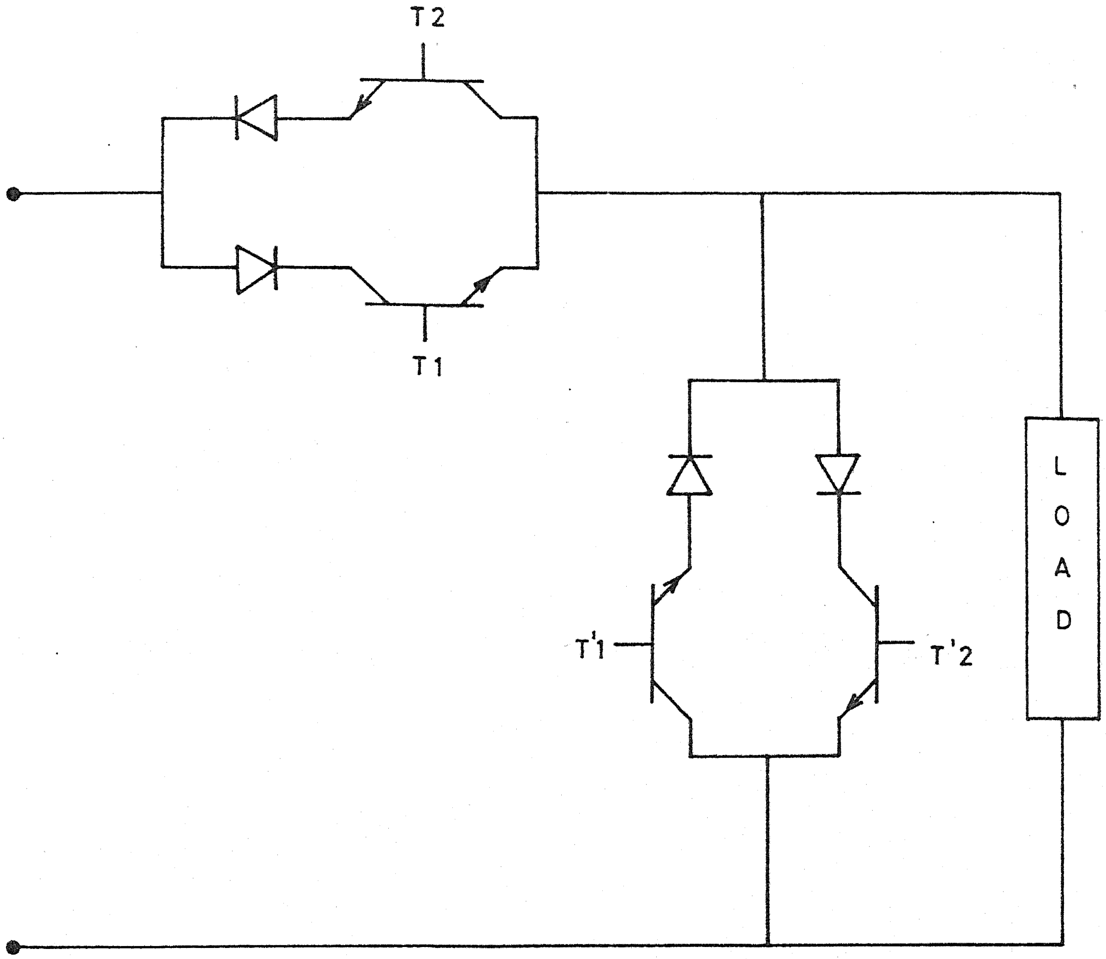


FIG. 2.4 TRANSISTORISED SYMMETRICAL VOLTAGE COPPER.

(IC) with Darlington configuration.

Fig. 2.5 shows the actual circuit of MJ 10009. This transistor is given large enough current which brings the transistor into the saturation region. In this mode of operation, the transistor acts as a switch with very low voltage drop across it. This chopper circuit needs four transistors in one phase and in total 12 transistors for three phase induction motor. This is an expensive circuit. A modified circuit is used which needs only two transistors in one phase.

This modified circuit is shown in Fig. 2.6. In both main line and freewheeling path a rectifier is used. This rectifier rectifies the ac current, thus only one transistor is required in each path. This circuit has the following advantages.

1. Two transistors are needed instead of four for each phase. It is therefore more economical.

2. It can be seen from the waveforms of Fig. 2.3 that the current changes direction in the power interval. Depending upon the polarity of the current, proper transistor is to be turned on. This needs current sensing in the circuit. But this is not required with the two transistors chopper because of the presence of the rectifier. The control circuit becomes much simpler with the two transistor ac chopper.

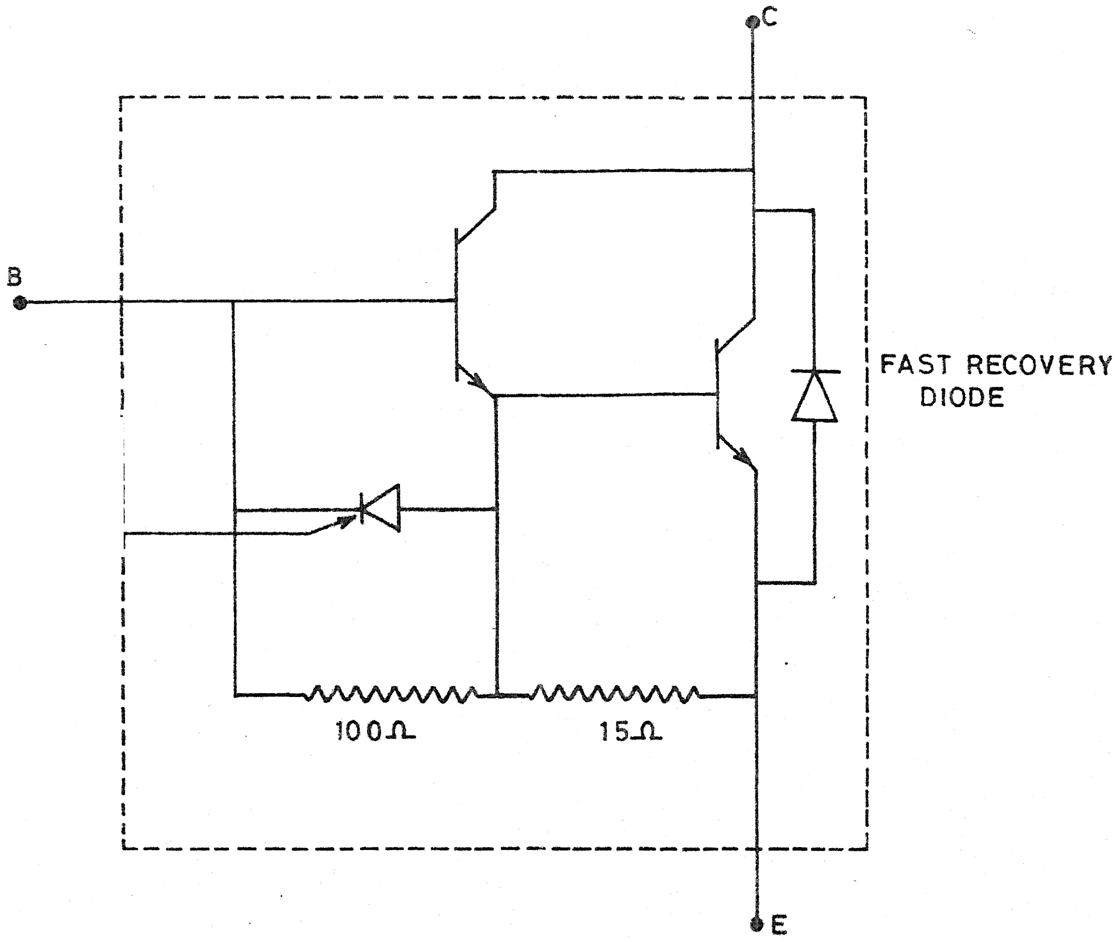


FIG. 2.5 INTERNAL CIRCUIT OF MJ 10009 TRANSISTOR.

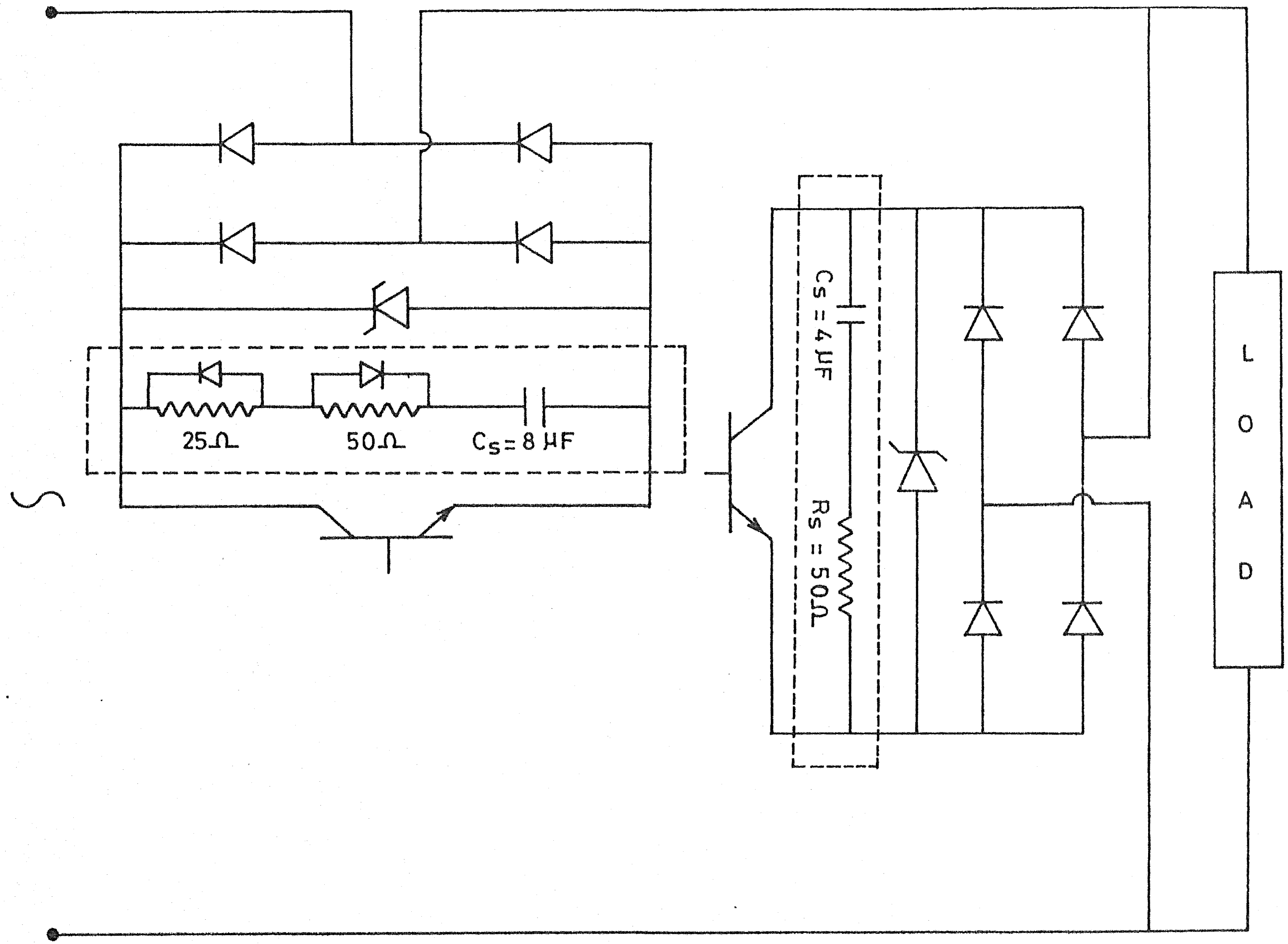


FIG. 2.6 MODIFIED SYMMETRICAL VOLTAGE CHOPPER.

The symmetrical voltage chopper of Fig. 2.6 provides satisfactory operation with active load under regenerative operation. This may occur in the case of on induction motor driving a hoist or a crane. In some portion of the load cycle, the induction machine acts as a generator and the chopper operates satisfactorily. A current sensor is however required for the chopper in Fig. 2.4.

In the ac chopper of Fig. 2.6 the incoming transistor can not be turned on at the instant when the outgoing transistor is conducting. If it is so, the source will be short circuited. To ensure satisfactory operation free from short circuit, a short delay is provided for the incoming transistor. During this delay a large voltage may build up which may damage the transistors. An alternative path is provided by the snubber circuit comprising of resistance and capacitance (R-C) connected in parallel with each transistor. Whenever a delay is given the interrupted current passes through this snubber circuit. It will be assured that the current will remain constant during the delay which is of the order of few μ secs. The initial voltage across the snubber circuit is

$$V_s = R_s I$$

where V_s is the voltage across the snubber circuit, R_s is the resistance of the snubber circuit, and I is the load current.

At the end of the interval, the voltage across the device is

$$V_s = I R_s + \frac{I T_d}{C_s}$$

where C_s is the capacitance of the snubber circuit and T_d is the time delay interval.

At the end of the delay interval the other transistor is turned on. At this instant C_s may not be charged to the supply voltage. This will provide a a path for the incoming transistor for a short time, and the equivalent circuit representing this condition is shown in Fig. 2.7. The rectifier is not shown for simplicity. Considering the worst condition it will be assumed that the transistor is turned on when the supply voltage is at its peak value, and there is no charge on the capacitor. The current through the snubber circuit will then be limited by the resistance R_s. The total current through the transistor will be sum of the load current and the current through the snubber circuit of the other transistor. The values of C_s and R_s are taken such that during the delay the voltage across the transistor does not exceed the safe limit, and also the current through the other transistor at the end of the delay should not exceed the specified peak value. From the safety considerations, these voltage and current limits must be smaller than the device ratings.

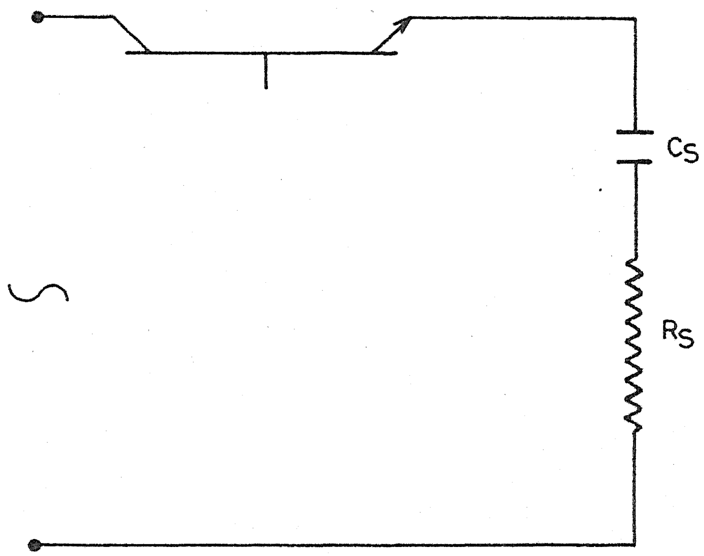


FIG. 2.7 CIRCUIT SHOWING ADDITIONAL CURRENT FLOWING THROUGH THE TRANSISTOR DUE TO SNUBBER.

Over voltage may also arise due to switching on or off somewhere in supply system. The transistor being a semiconductor device is very sensitive to over voltage transient even though it may last for a short duration. For protection against an overvoltage, Selenium voltage suppressors or zener diodes are used. The zener diodes shown in Fig. 2.6 serves this purpose. The breakdown voltage of the zener diode should be less than that of the transistor.

2.3 Control Circuit

Fig. 2.8 shows the circuit which generates control pulses for the chopper. There are three main parts in the circuit i.e.

1. Symmetrical pulse generator
2. Monostable multivibrator
3. Driver Circuit

2.3.1 Symmetrical Pulse Generator

This comprises one step down transformer (220/6.3-0-6.3), a rectifier, and a comparator. In the comparator the rectified voltage is compared with a variable dc voltage. This provides a symmetrical pulse output of variable width in the each half cycle. These pulse are provided with a short (20 μSec) delay at the rising edge and fed to the main transistor of the chopper.

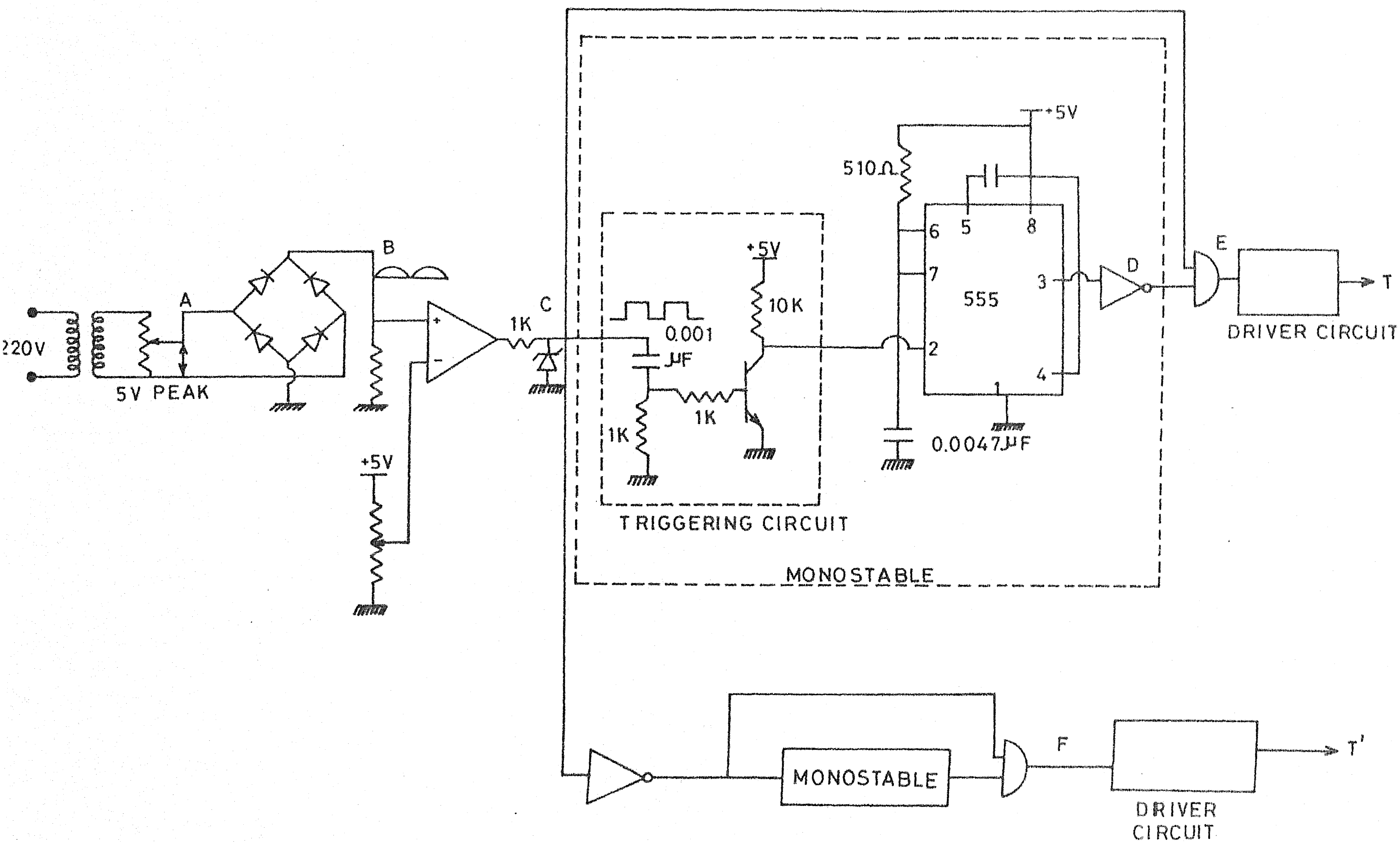


FIG. 2.8 CONTROL CIRCUIT FOR SYMMETRICAL VOLTAGE CHOPPER.

2.3.2 Monostable Multivibrator

This short duration pulse is obtained by a monostable multivibrator. A NE555 timer is used for this purpose. This monostable needs a triggering pulse of very short time (2 - 3 μ secs.), which is obtained by a triggering circuit shown in the same figure. The monostable output is ANDed with the pulse at the point C. Fig. 2.9 shows different waveforms marked at the points in Fig. 2.8.

2.3.3 Driver Circuit

The most important requirement in the chopper is that the pulse which is provided to the transistor should be isolated from the main circuit. In thyristored circuits, the isolation is provided by pulse transformers. For transistors, pulse transformers cannot be used because the available pulse transformers are not capable of carrying continuous current which the transistors need.

Isolation in that case is obtained by an opto-isolator. The input and output of the opto-isolator are isolated to each other. But the output of the isolator depends upon the input. Fig. 2.10 shows such a current 5082-4370/1 is an isolator chip. Whenever there is a high pulse at the input, D_1 conducts and it emits light. D_2 is also a photo diode, as light strikes

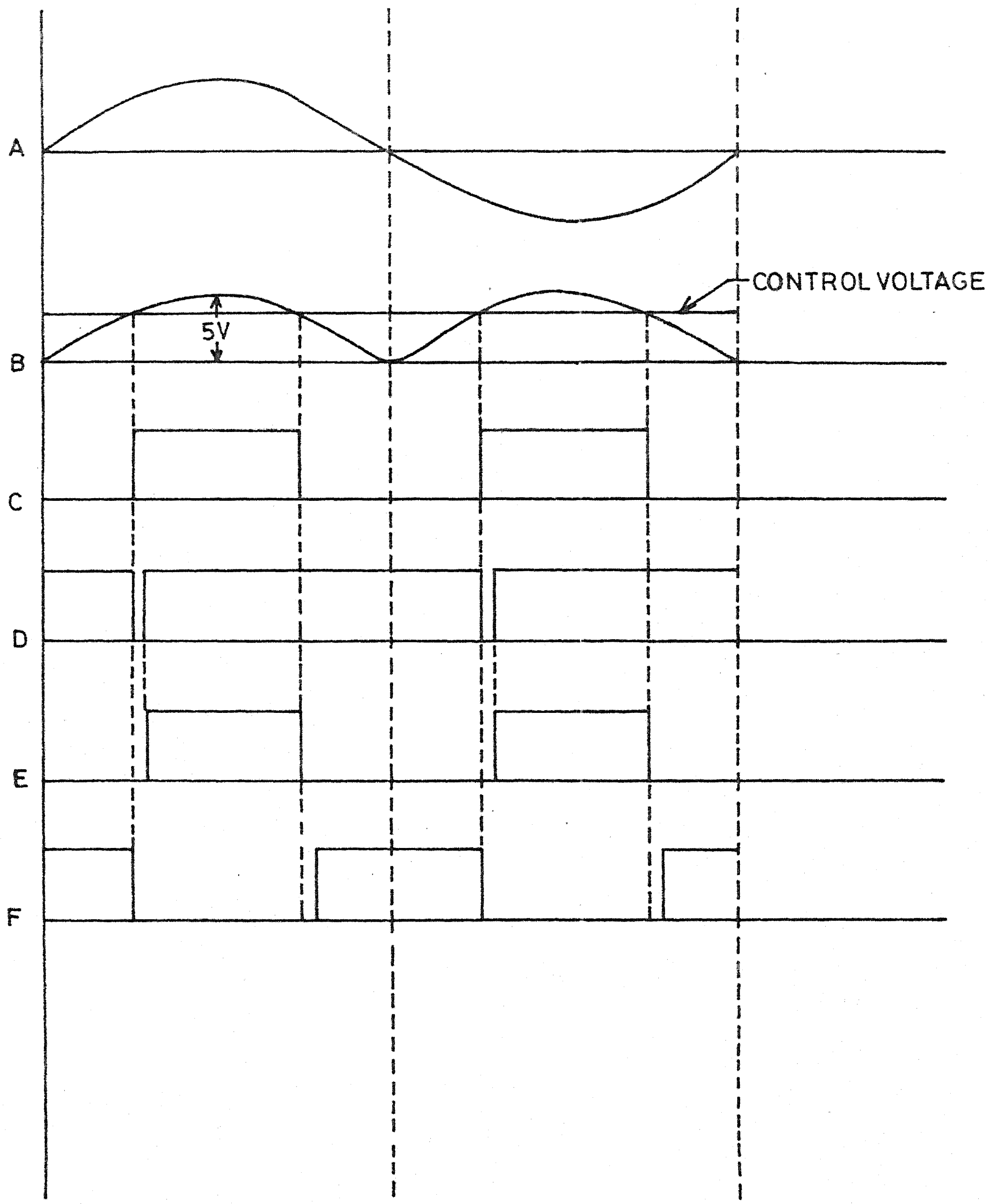


FIG. 2.9 WAVEFORMS AT DIFFERENT POINTS IN CONTROL CIRCUIT.

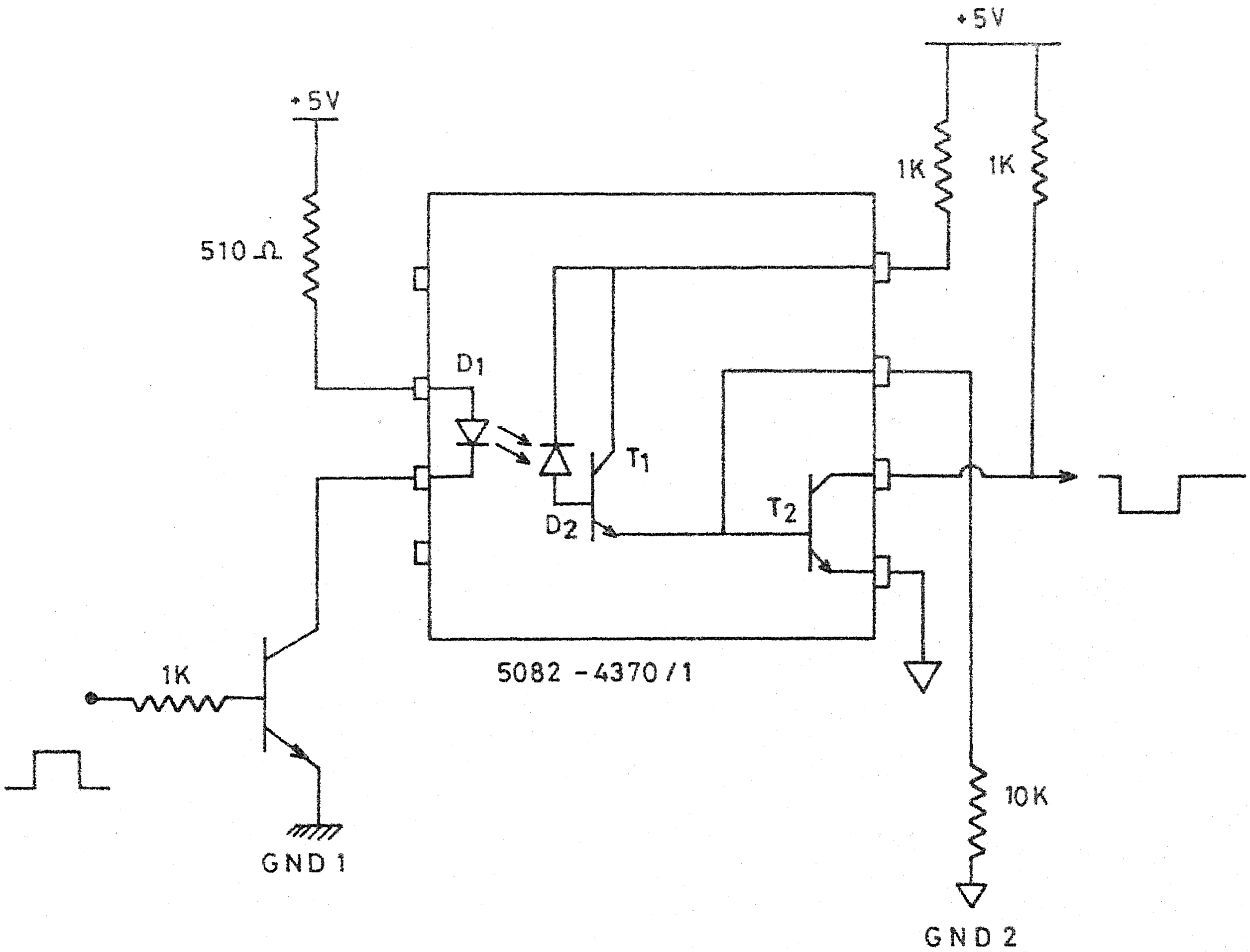


FIG. 2.10 OPTO-ISOLATOR

the diode D_2, it also starts conduction and provides base current to T_1, which drives T_2. As T_2 goes into conduction the output goes low. Whenever input pulse is low, D_1 does not conduct thus transistors go into off state, hence the output becomes high. For the output of the isolator to be isolated from input, the output supply is separate. Fig. 2.11 shows the separate power supply. For this purpose a transformer (220/6.3-0-6.3, 1A) with a bridge rectifier and a capacitor filter is used.

Fig. 2.12 shows the driver circuit. The dc supply is provided from the circuit as described earlier.

The reference point of the power supply is shown by GND2. When the point A is high, B goes low. C is at higher voltage compared to B. This turns the transistor T_1 'on' and T_2 'off', base of the power transistor becomes forward biased, and the transistor goes into saturation. Whenever A is at low, point D is at -1.4 volts, which turns off the power transistor. With a negative voltage at the base of the power transistor the breakover voltage increases.

2.4 Over Current Protection

Connected to the driver circuit is a circuit for protecting the power transistor. If there is an excessive current

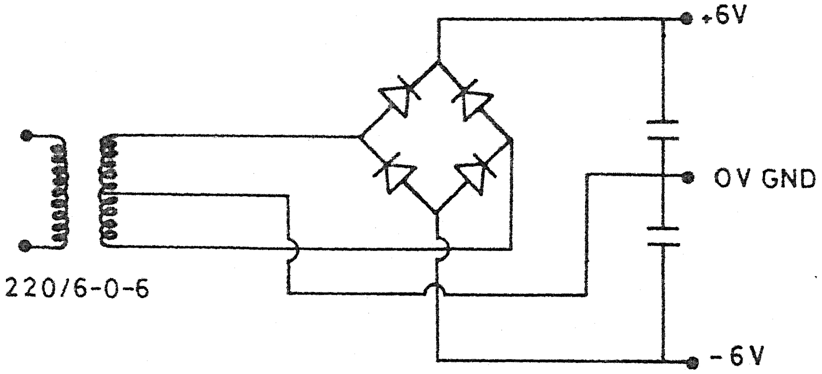
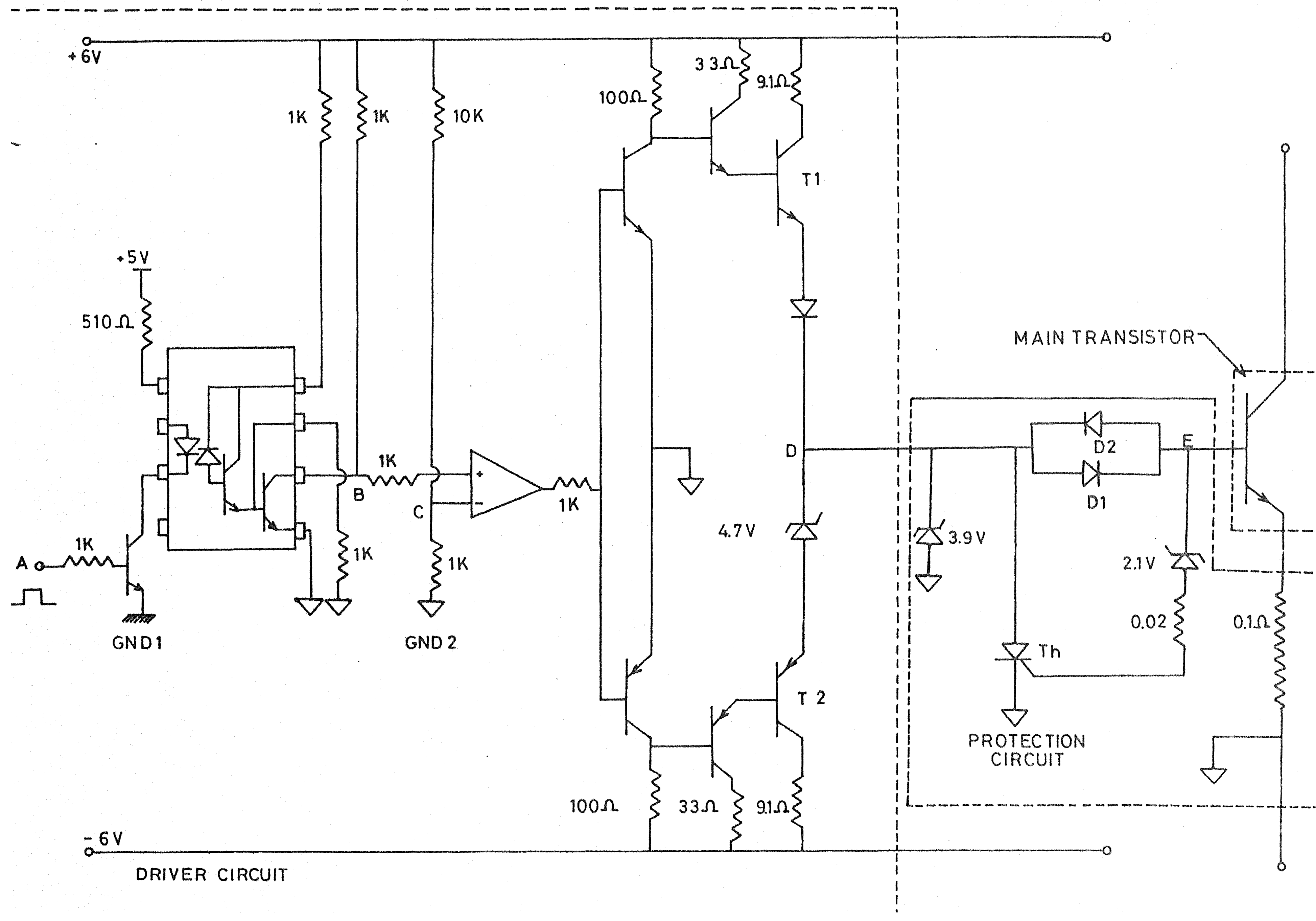


FIG. 2.11 POWER SUPPLY


+6V
1K
1K
10K
100Ω
3 3Ω
9.1Ω
T1
+5V
510Ω
MAIN TRANSISTOR
D
1K
D2
E
B
C
1K
D1
4.7V
3.9V
1K
A
1K
1K
2.1V
0.02
0.1Ω
GND1
GND 2
Th
T 2
PROTECTION
CIRCUIT
100Ω
33Ω
9.1Ω
-6V
DRIVER CIRCUIT

or short circuit through the transistor. In this chopper, there is a possibility of short circuit if the two transistors conduct simultaneously. The protection circuit is shown in Fig. 2.12. A resistance of 0.1 ohm is connected between the emitter and the ground of the dc power supply. As the load current increases, the voltage at the point E also increases. A zener and a resistance are connected between the gate of the **thyristor** T_h and the base of the power transistor. Whenever the current increases above certain value, the zener breaks-down and supplies the current to the gate of the thyristor T_h which then turns on. The voltage at the point D becomes 1 V. The diode D_1 is connected in the circuit so that at 1 V the base of the transistor does not get enough current. As for a diode to conduct 0.7 volt is required. Power transistor is already a Darlington pair. So three diodes in a series would need 2.1 volts for conduction. As a result, the transistor goes into 'off' state as the thyristor T_h turns on. The diode D_2 is connected to provide a path for the charges in the base region whenever the transistor is turned off. One zener is connected across the thyristor T_h. This zener will not allow the load current to rise more than 18A. If the current reaches 18A, the voltage at the point D will be 3.9 volts, and at this voltage the zener would start conduction, and any further rise in the transistor current will result in a reduction

in the base current, which will take the power transistor into the active region. This zener provides an additional protection.

In case the thyristor T_h does not turn on fast then the zener limits the transistor current and takes it into active region. In active region the transistor can remain for few μsecs. In the mean time thyristor T_h will get turned on. But the current beyond the limit damages the transistor very fast.

2.5 Phase Angle Controller

Performance of the symmetrical voltage chopper with R-L load was compared with the phase angle controller. Fig. 2.13 shows the control circuit for the phase angle controller. Fig. 2.14 shows the waveforms at different points marked in Fig. 2.13. The phase voltage is stepped down and fed to zero crossing detector (ZCD). For positive half cycle ZCD1 outputs positive voltage and for the negative half cycle it outputs negative voltage, which is close to the supply voltage of the comparator. The positive output is integrated in a R-C circuit and negative half is clipped by a diode. The output is compared with a dc voltage in another comparator. This provides a variable width output. The positive half is fed to a differentiator which has output in the form of positive and negative

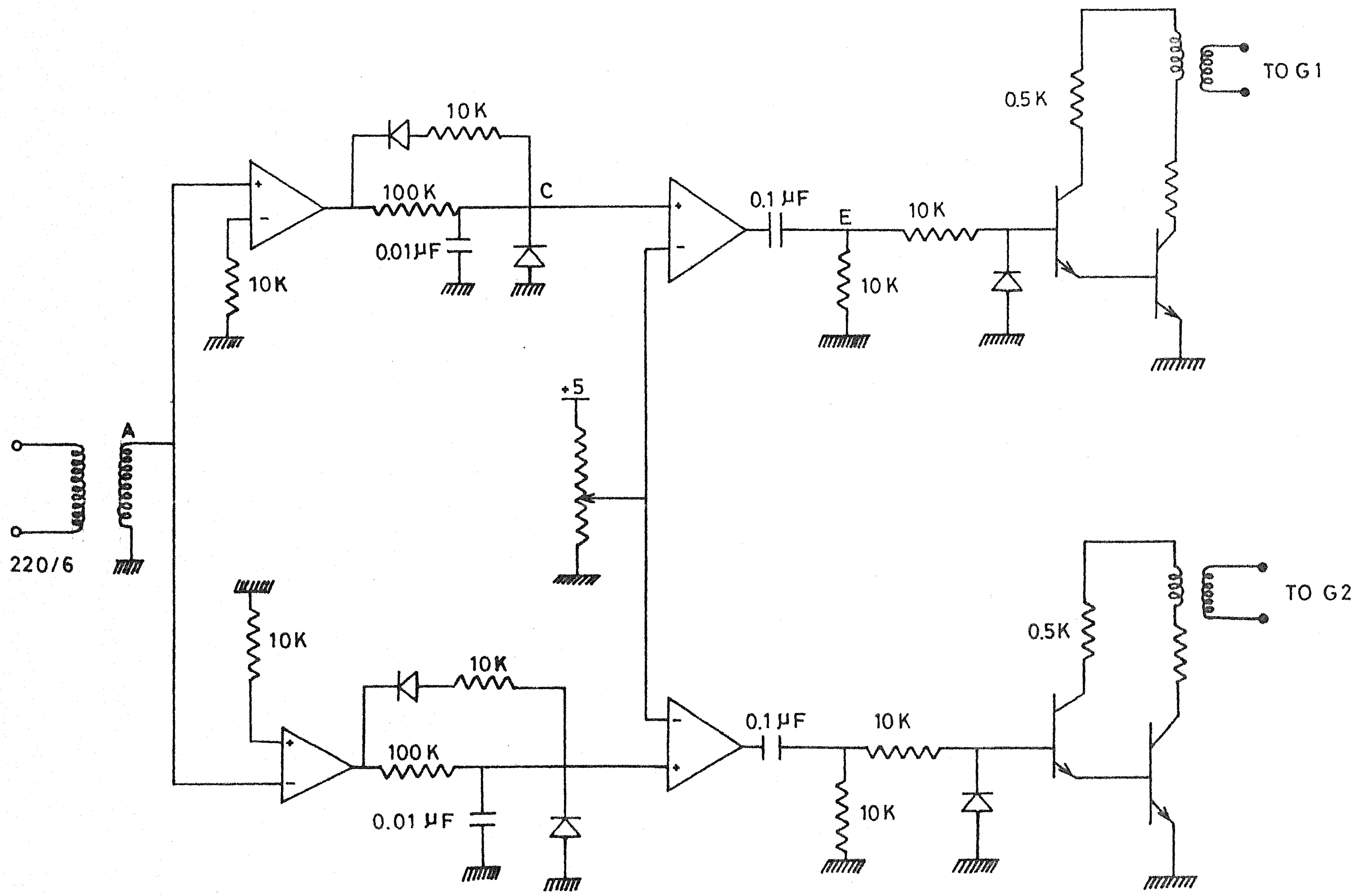


FIG. 2.13 CONTROL CIRCUIT FOR PHASE ANGLE CONTROLLER.

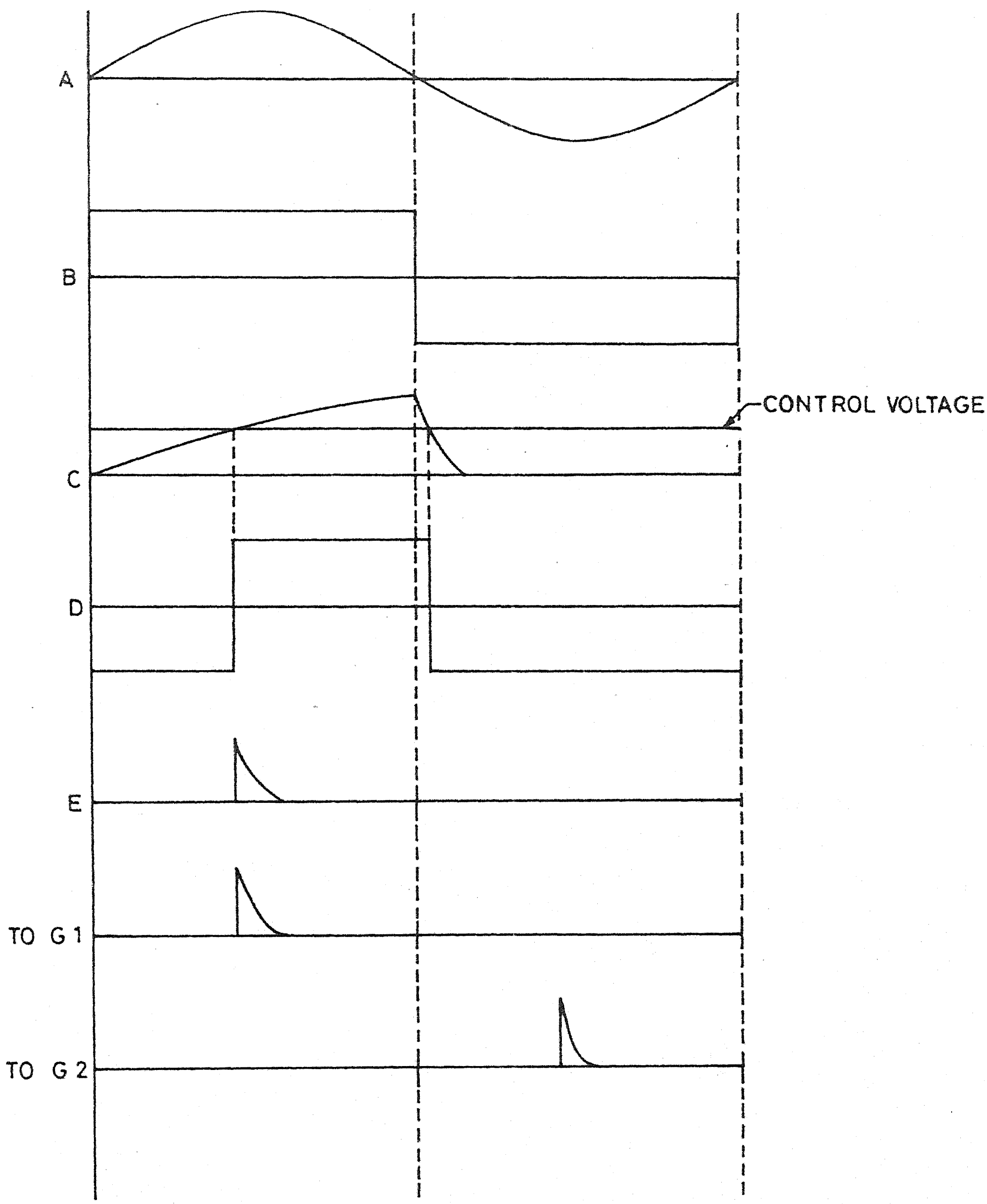


FIG. 2.14 WAVE FORMS AT DIFFERENT POINTS IN CONTROL CIRCUIT.

spikes. The negative spike is clipped and the positive spike is fed to the base of the drive circuit. The output of the driver circuit is transferred to the gate of the thyristor through a pulse transformer. Similar circuit is used for the other thyristor which conducts in the negative half cycle.

The experimental setup for the symmetrical voltage chopper is shown in Fig. 2.15.

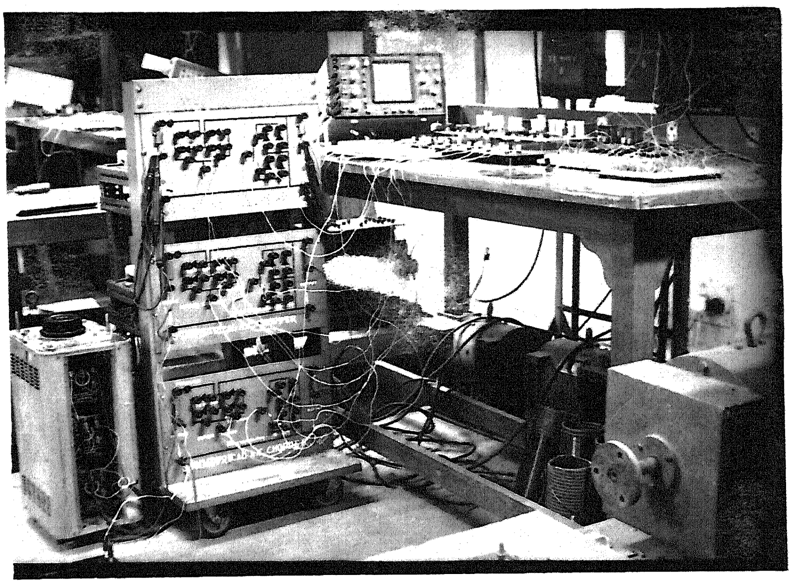


Fig. 2.15 Experimental Set up

CHAPTER 3

COMPUTATION OF MOTOR PERFORMANCE

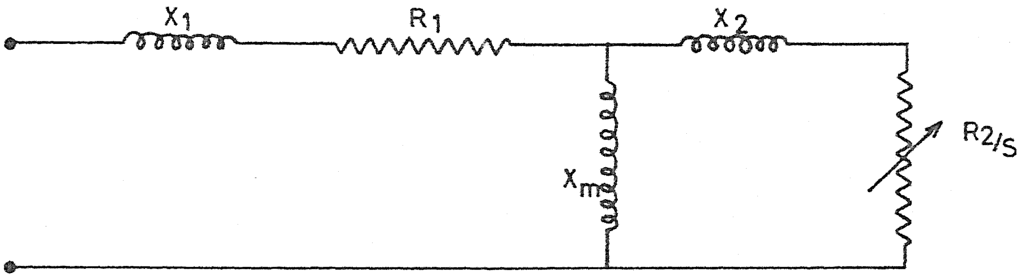
In this chapter the performance of the motor is obtained by the digital simulation of the motor. A model similar to that of the transformer is used which is found in the literature[5]. Having known the motor voltage, the harmonic analysis is carried out.

3.1 Mathematical model for Induction Motor

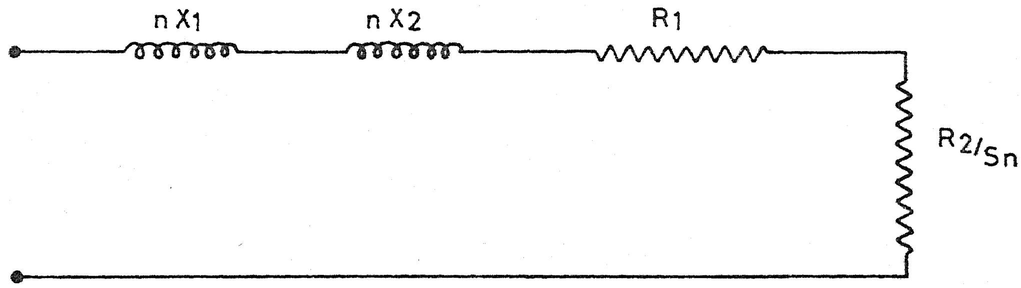
Since the voltage supplied to the motor is not sinusoidal, it contains voltage harmonics besides the fundamental. There are positive sequence, negative sequence, and zero sequence harmonics.

The fundamental and positive sequence harmonics give rise to m.m.fs. which rotate in the same direction thereby producing torques in the same direction. A negative sequence harmonic give rise to the flux in opposite direction thus producing negative torque. The zero sequence harmonic does not produce any torque.

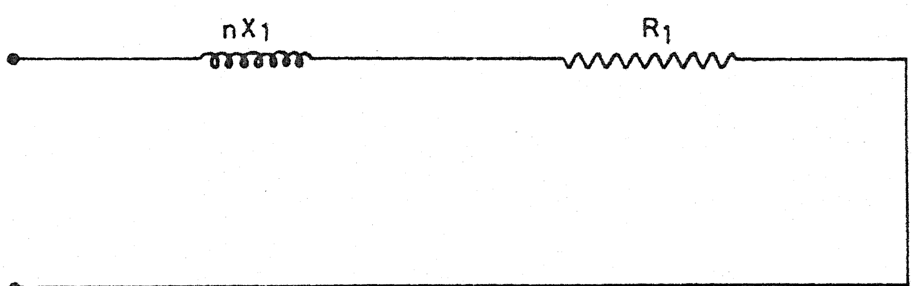
Fig. 3.1 shows the equivalent circuits for three types of harmonics. These equivalent circuits are idealized and simplified for the motor. Parameters are assumed to be



(a)



(b)



(c)

FIG. 3.1 EQUIVALENT CIRCUITS OF INDUCTION MOTOR

(a) POSITIVE SEQUENCE

& NEGATIVE SEQUENCE

(c) ZERO SEQUENCE

(a) FOR FUNDAMENTAL

lumped and both iron loss and variation in the resistance due to skin effect are neglected.

For the positive and the negative sequence harmonics, the slip S_n is close to unity. The magnetising reactance being much more than the secondary impedance may be neglected. The slip for the positive and the negative sequence harmonics is given by two different expressions.

For positive sequence harmonics

$$S_n = \frac{n-1+S}{n}$$

where $n = 7, 11, 19, ---$

and for the negative sequence harmonics

$$S_n = \frac{n+1-S}{n}$$

where $n = 5, 13, 17, ---$

and S is the slip for the fundamental.

The zero sequence harmonics are present because of the neutral connection in the stator. The zero sequence current in all phases of the motor are in phase. The net space flux produced by any zero sequence harmonic current is zero, and hence these currents are limited to the stator circuit only. The reactance for the zero sequence harmonic for the motor is a complicated function of the stator winding design, slot dimensions etc.

Here the zero sequence reactance is taken to be equal to the stator leakage reactance only [5] .

3.2 Harmonic Analysis

The shaded part of Fig. 3.2 shows the motor voltage for a particular value of α. Different harmonic components and the fundamental are found by the following relations.

$$A_n = \frac{1}{\pi} \int_0^{2\pi} v(\theta) \, \text{Cos} n\theta \, d\theta \tag{3.1}$$

and

$$B_n = \frac{1}{\pi} \int_0^{2\pi} v(\theta) \, \text{Sin} n\theta \, d\theta \tag{3.2}$$

where $v(\theta)$ is the instantaneous motor voltage.

Harmonic voltage is given by

$$V_n = \sqrt{A_n^2 + B_n^2} / \sqrt{2} \tag{3.3}$$

where n = 1, 3, 5, - - -

It can be shown that for even values of n, $V_n = 0$.

From the harmonic analysis of the output voltage, the rms value of the fundamental is

$$V_1 = V(\pi - 2\alpha + \text{Sin } 2\alpha)/\pi \tag{3.4}$$

where V is the input rms voltage.

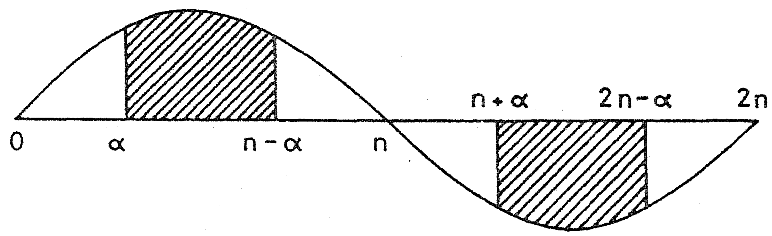


FIG.3.2 LOAD VOLTAGE

For the other harmonics

$$V_n = \frac{2V}{\pi} \quad \frac{\sin(n+1)\alpha}{(n+1)} - \frac{\sin(n-1)\alpha}{(n-1)} \qquad (3.5)$$

The instantaneous motor current is

$$i_m(\theta) = \sqrt{2} \sum_{n=0}^{n=\infty} I_n \sin n(\theta - \phi_n) \qquad (3.6)$$

The fundamental, positive, negative, and zero sequence harmonic components are :

$$I_1 = \frac{V_1}{C_1} \angle \phi_1 \qquad (3.7)$$

For the positive and the negative sequence harmonics

$$I_n = \frac{V_n}{C_n} \angle \phi_n \qquad (3.8)$$

For the zero sequence harmonics

$$I_{no} = \frac{V_{no}}{C_{no}} \angle \phi_{no} \qquad (3.9)$$

From the equivalent circuits of Fig. 2.3 C_1, C_n and C_{no} are determined.

They are :

$$C_1 = R + JX \qquad (3.10)$$

where

$$R = \frac{R_1 \left[(\frac{R_2}{S})^2 + (X_2 + X_m)^2 \right] + (\frac{R_2}{S})^2 \; X_m^{\,2}}{\left[(\frac{R_2}{S})^2 + (X_2 + X_m)^2 \right]} \tag{3.11}$$

and

$$X = \frac{X_1 \left[(\frac{R_2}{S})^2 + (X_2 + X_m)^2 \right] + X_m (\frac{R_2}{S})^2 + X_2 X_m^{\,2} + X_m X_2^{\,2}}{\left[(\frac{R_2}{S})^2 + (X_2 + X_m)^2 \right]} \tag{3.12}$$

$$C_n = R_n + J\, X_n \tag{3.13}$$

where

$$R_n = R_1 + R_2/S_n \tag{3.14}$$

and

$$X_n = X_1 + X_2 \tag{3.15}$$

$$C_{no} = R_1 + j\, n\, X_1 \tag{3.16}$$

Torque produced by the motor is

$$T = \frac{3}{2\pi\, w_S} \left[\sum_{n=1,7,11,\ldots} \frac{I_{rn}^2}{n} \frac{R_2}{S_n} - \sum_{n=5,13,17,\ldots} \frac{I_{rn}^2}{n} \frac{R_2}{S_n} \right] \tag{3.17}$$

where w_S is the synchronous speed of the motor in rps corresponding to the fundamental frequency.

I_{rn} is the rotor current for the n^{th} harmonic. Power developed by the motor

$$P = T2\pi w_s(1 - S) \tag{3.18}$$

Efficiency

$$\eta = \frac{P}{P+\text{motor Cu loss}} \tag{3.19}$$

Total motor rms current

$$I_m = I_1^2 + I_3^2 + I_5^2 + ---- \tag{3.20}$$

Source current :

The motor current is divided into two parts by the chopper, one flows through the source and other through the freewheeling path. The source current is therefore different from the motor current and its harmonic spectrum would also be different.

The Fourier coefficients for the n^{th} harmonic are

$$A_n = \frac{1}{\pi} \left[\int_{\alpha}^{\pi-\alpha} i_m(\theta) \cos n\theta \, d\theta + \int_{\pi+\alpha}^{2\pi-\alpha} 2m(\theta) \cos n\theta \, d\theta \right] \tag{3.21}$$

$$B_n = \frac{1}{\pi} \left[\int_{\alpha}^{\pi-\alpha} i_m(\theta) \sin n\theta \, d\theta + \int_{\pi+\alpha}^{2\pi-\alpha} i_m(\theta) \sin n\theta \, d\theta \right] \tag{3.22}$$

Knowing the source current waveform, it is numerically integrated to obtain the Fourier coefficients. The fundamental and harmonic components in the source current are determined after calculating the coefficients. These are determined on a digital computer.

CHAPTER 4

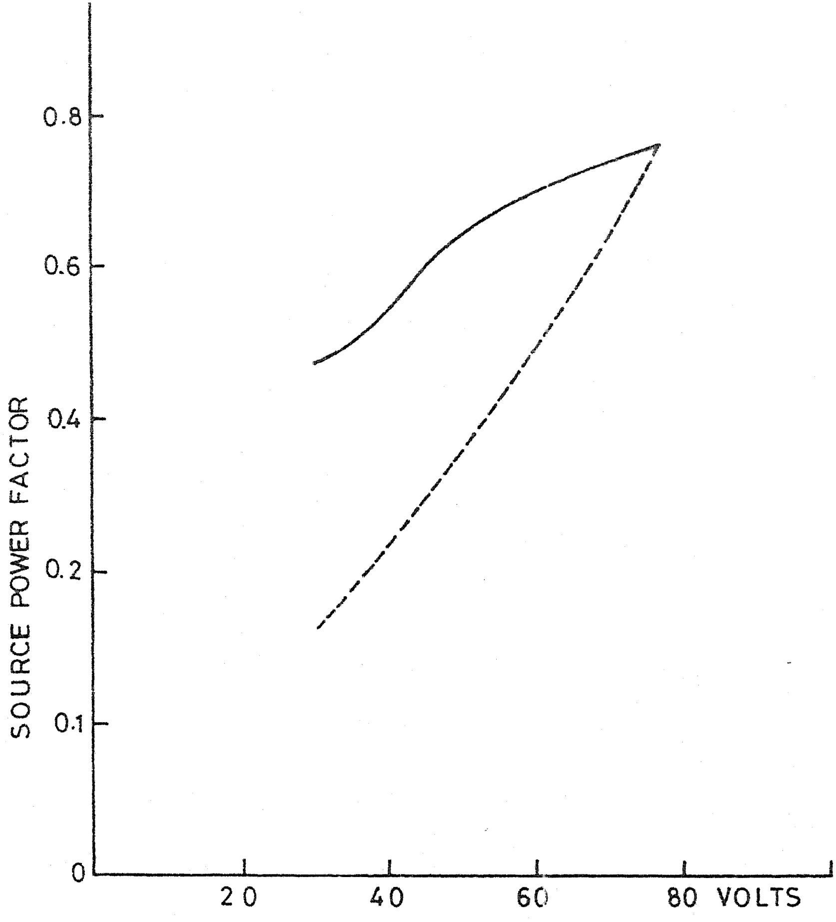
RESULTS AND DISCUSSIONS

4.1 Introduction

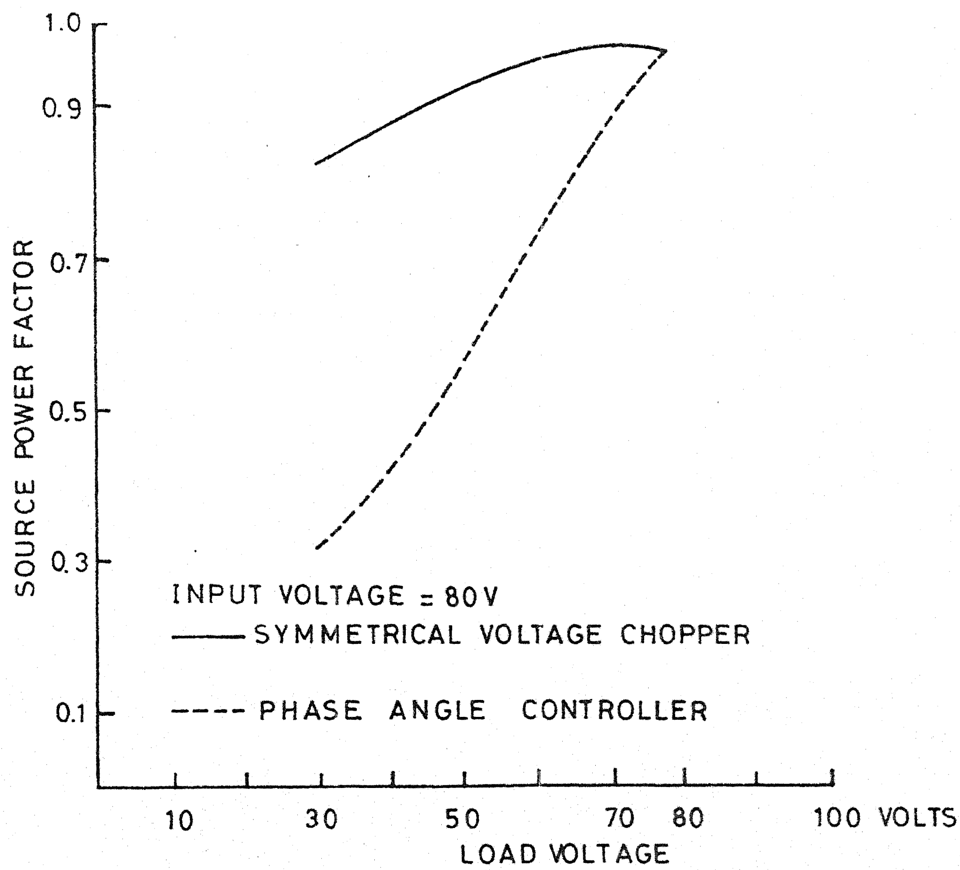
In this chapter theoretical and experimental results are compared. Passive (R-L) as well as active (Three-phase induction motor) loads are considered. For the R-L load, the performance characteristics with the phase angle controller are obtained and compared with the symmetrical voltage controller.

4.2 R-L Load

Fig. 4.1 shows characteristic relating the source power factor and the load voltage for two different loads. It is seen that at low voltages the source power factor for the phase angle controller is very poor but for the symmetrical voltage chopper it is comparatively high. For higher voltages the power factor is nearly same for both controllers. For the phase angle controller at low voltages the firing angle is delayed which results in poor displacement factor and high harmonic content, these both factors result in poor source power factor. But for the symmetrical voltage chopper the displacement factor reaches unity with increasing firing angle,



(a)



(b)

FIG.4.1 SOURCE POWER FACTOR VERSUS LOAD VOLTAGE.

hence the source power factor is high even with high harmonic content.

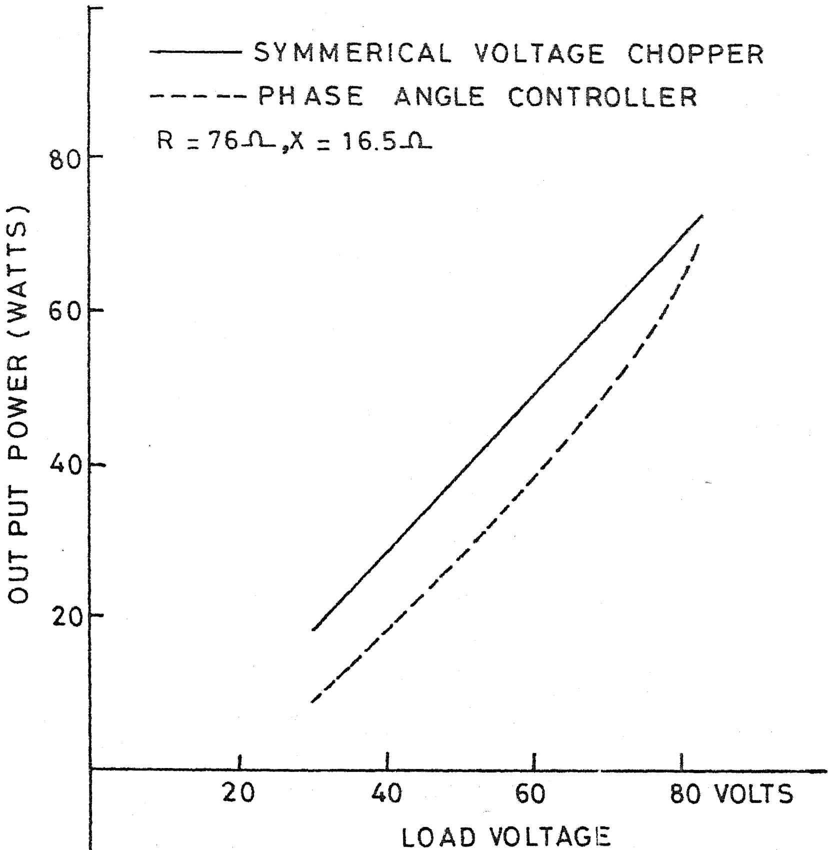
Fig. 4.2 shows the variation of output power with the output voltage. In case of the phase angle controller, the energy stored in the load inductance in any of the half cycles is partly fed back to the source in the next half cycle, while in the case of the symmetrical voltage chopper the stored energy is utilized in the load itself during freewheeling. Therefore the power fed to the load for the same voltage is more in case of the symmetrical voltage chopper.

4.3 Active Load

The performance characteristics of a three-phase induction motor with the symmetrical voltage chopper are given in this section. The details of the three-phase induction motor are given in Appendix II.

4.3.1 Motor Harmonics

The slip for any harmonic is close to unity, and it does not vary much with the motor speed. Further the reactance at a harmonic frequency is much more than the resistance. As a result the harmonic current is virtually independent of the speed.



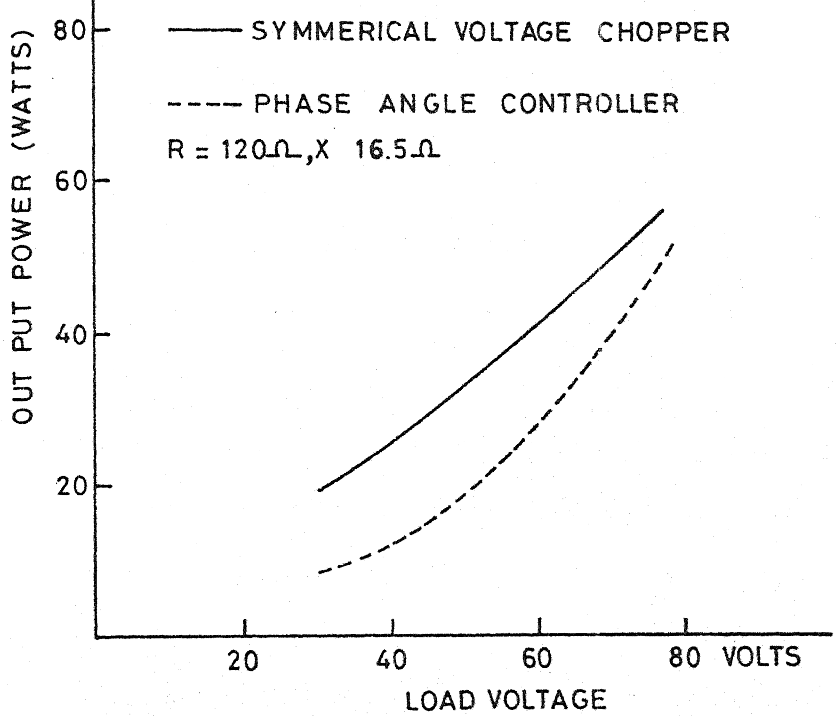


FIG. 4.2 LOAD POWER VERSUS LOAD VOLTAGE.

The harmonic current depends only on the firing angle.

Fig. 4.3 depicts the variation of different harmonics with the symmetrical firing angle. It can be seen that the third harmonic is very high. The impedance for the third harmonic is offered by the stator circuit only. The third harmonic current is maximum when the firing angle is 60°. An additional reactance is connected in the stator circuit to reduce the third harmonic without significantly affecting the fundamental current. The other harmonic currents also decrease due to the presence of this additional reactance. This can be clearly seen from Fig. 4.3. The motor performance improves with the additional inductance as can be seen later.

4.3.2 Source Harmonics

Unlike the motor harmonics, the harmonics in the source current are dependent on the speed of the motor, because source harmonics are dependent on the shape of the source current which is affected by the motor fundamental current, which in turn is dependent on the speed. The source harmonics are shown in Fig. 4.4 for a particular slip equal to 0.02. The third harmonic is quite predominant throughout the range of the firing angle except at very low and very high firing angles.

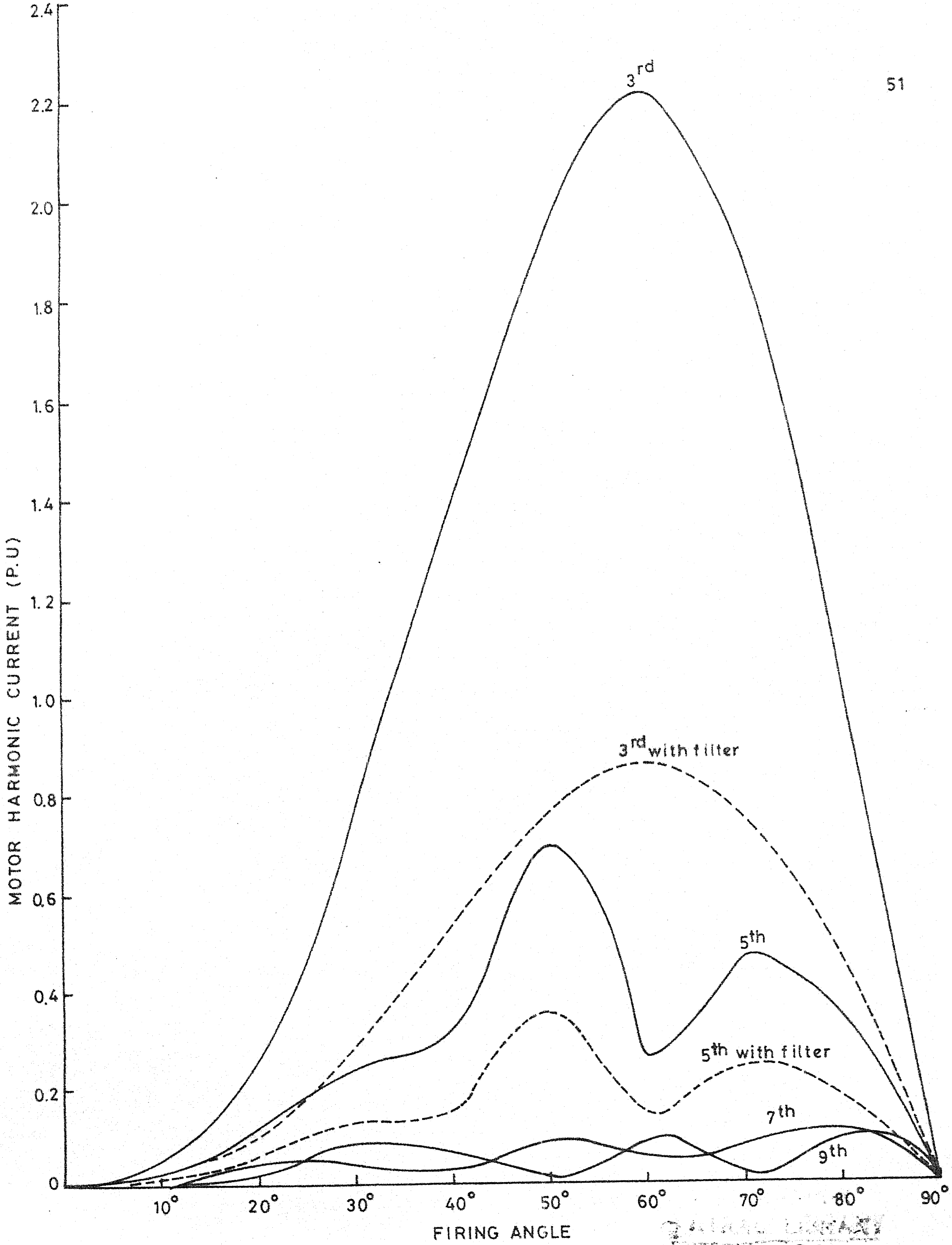


FIG.4.3 MOTOR HARMONICS VERSUS FIRING ANGLE.

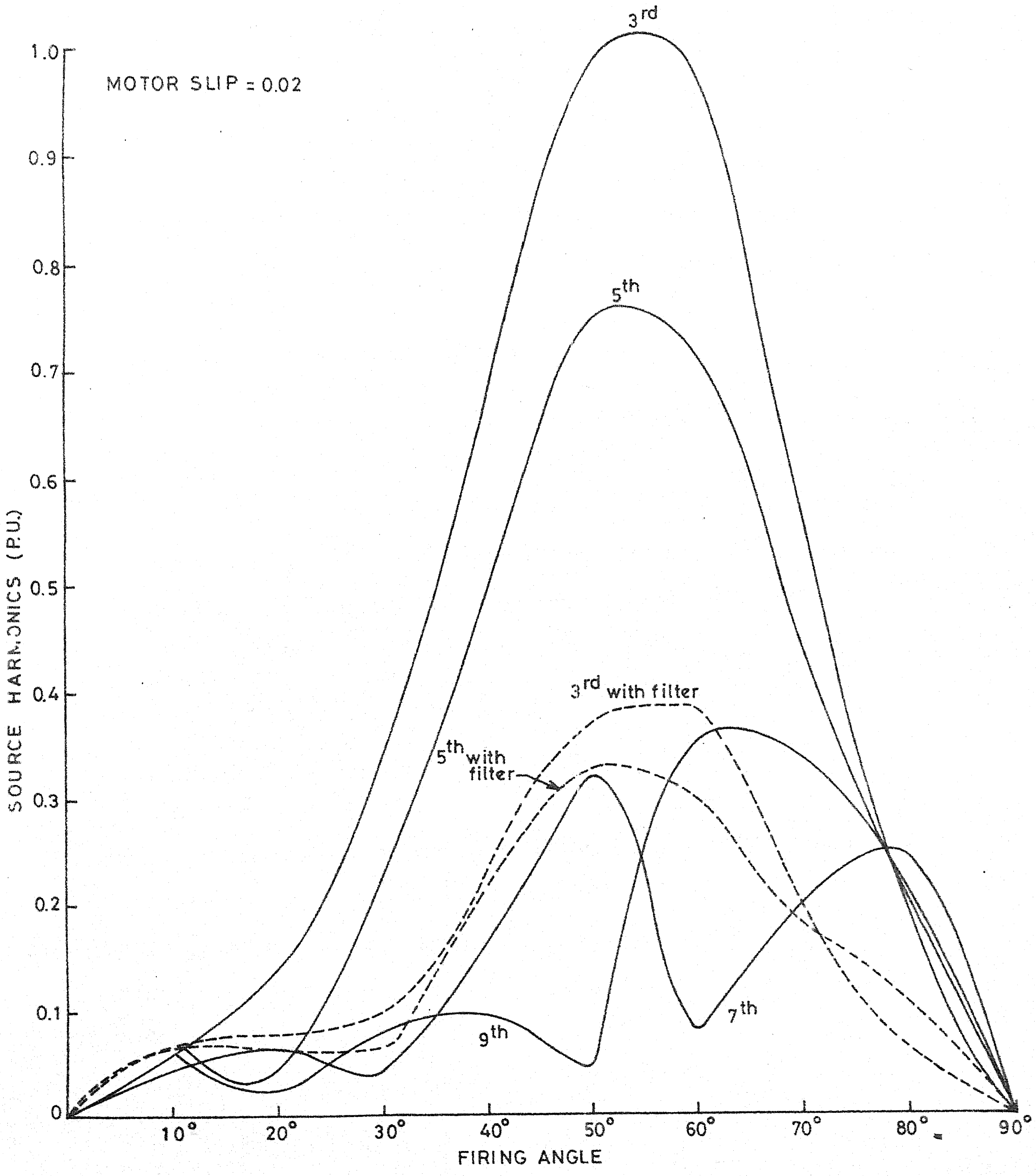


FIG. 4.4 SOURCE HARMONICS VERSUS FIRING ANGLE.

All these harmonics have lower amplitudes lower than those in the motor current. The additional inductance has the filtering effect on all the harmonics as can be clearly seen in Fig. 4.4.

4.3.3 Motor and Source Currents

Fig. 4.5 shows the variation of the motor current and the source current with slip for different firing angles. As it is clearly seen that the source current is less than the motor current, this is because of the freewheeling. Fig. 4.6 shows the curves with the additional inductance.

4.3.4 Output Torque

Fig. 4.7 shows the torque-slip characteristic of the motor driven by the symmetrical voltage chopper. The torque-slip curves are shown with and without filter. Although the torque decreases with the presence of filter, the decrease is not significant upto the breakdown torque. But beyond the breakdown torque, the decrease in the torque is significant . Since the starting torque decreases considerably, the drive system is particularly useful for applications requiring low starting torque, such as fans, pumps, and blowers.

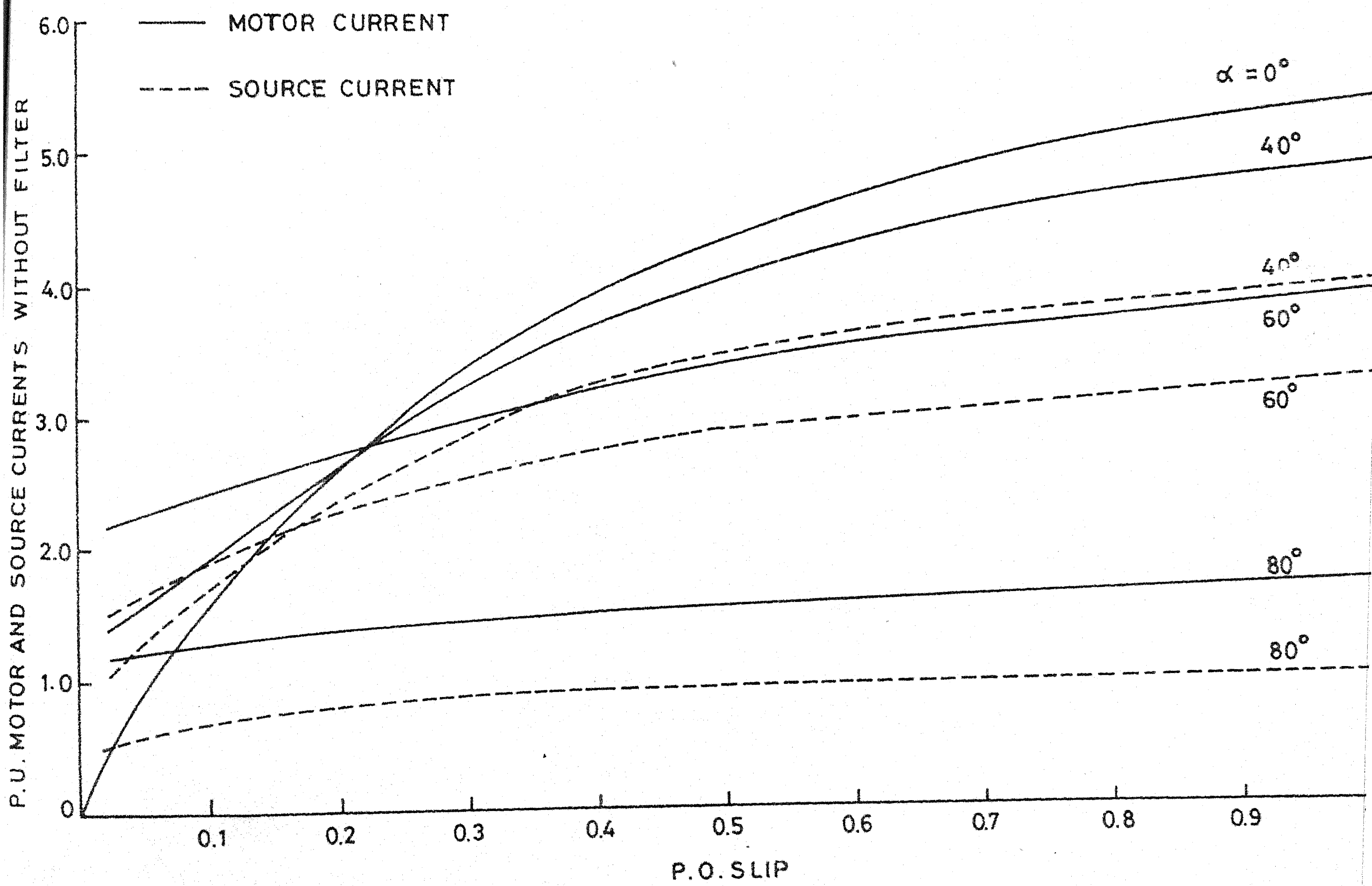


FIG. 4.5 MOTOR AND SOURCE CURRENTS VERSUS SLIP FOR DIFFERENT FIRING ANGLES WITH FILTER.

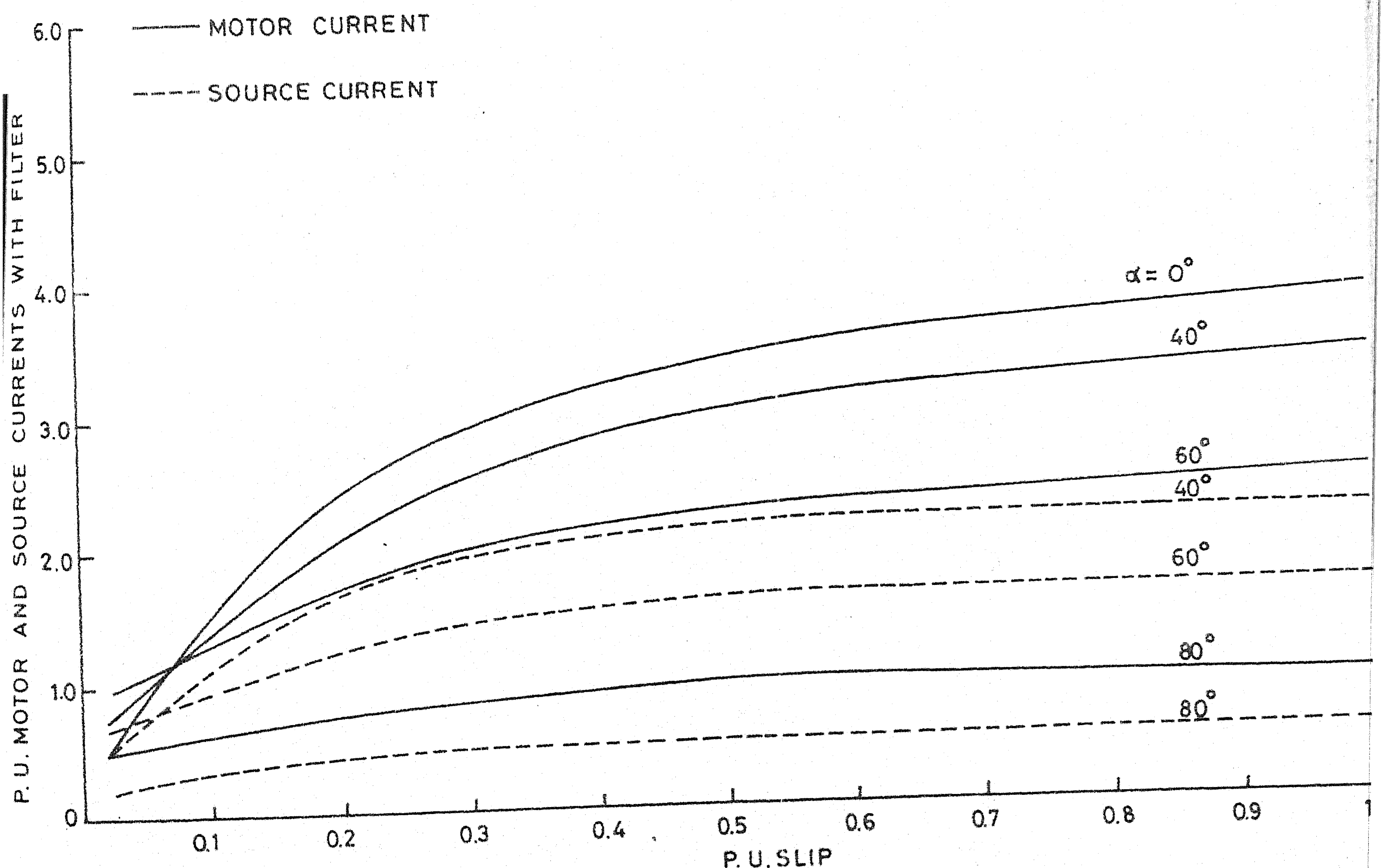


FIG. 4.6 MOTOR AND SOURCE CURRENTS VERSUS SLIP FOR DIFFERENT FIRING ANGLES WIT
FILTER.

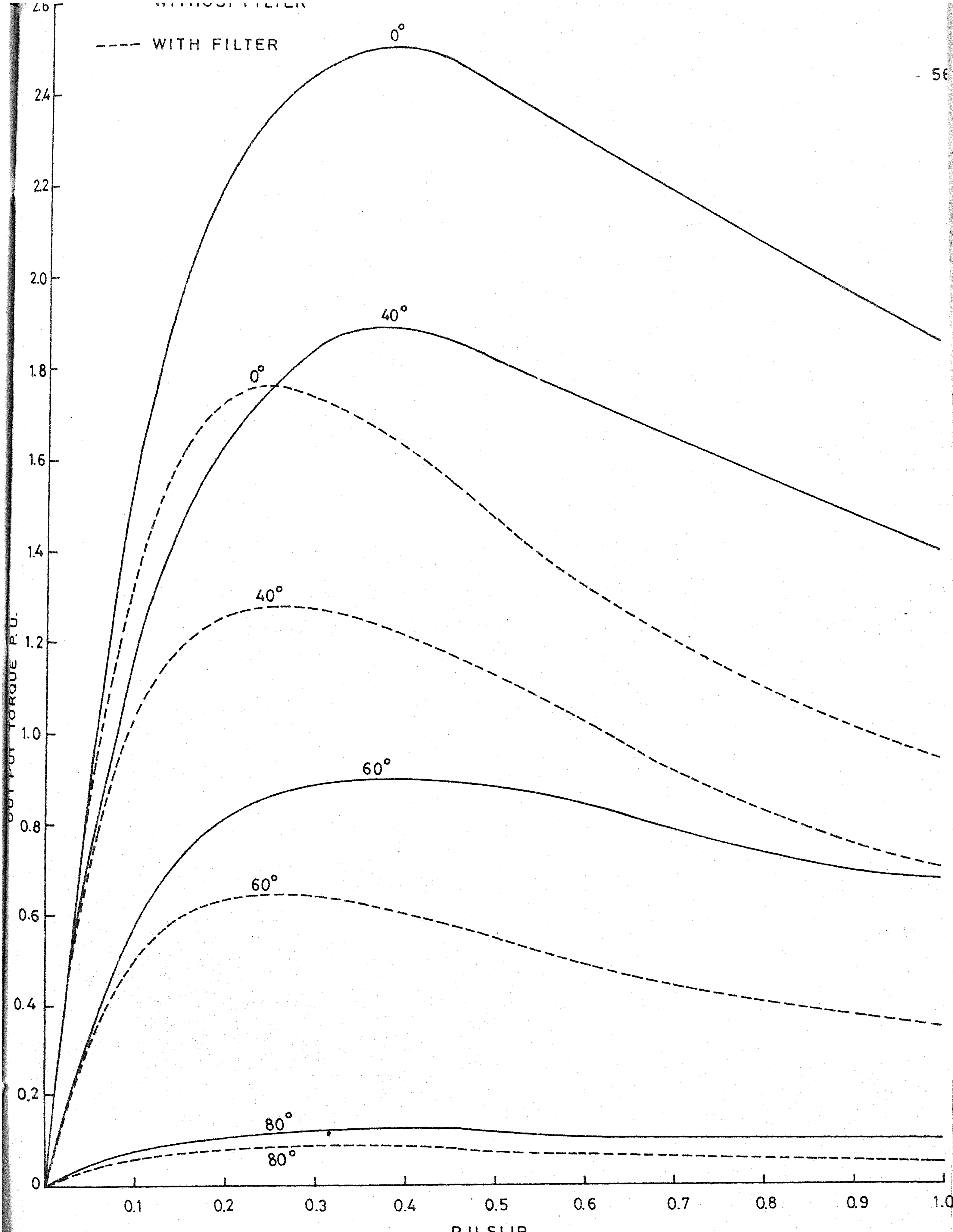


FIG. 4.7 MOTOR TORQUE VERSUS SLIP FOR DIFFERENT FIRING ANGLES.

4.3.5 Output Power

Fig. 4.8 shows the variation of the output power with slip at the shaft of the motor for different firing angles for both cases, with and without filter are considered. There is a reduction in the peak power supplied by the motor for any firing angle with the filter. Around rated slip (0.053 p.u.) the reduction in the output power is negligible.

4.3.6 Efficiency

The motor efficiency-slip characteristic is shown in Fig. 4.9 for different firing angles for both cases. The loss due to harmonics in the motor without the filter is very high which results in poor efficiency as the firing angle increases. The efficiency improves significantly in the presence of the filter.

4.3.7 Source Displacement Factor

The displacement factor is cosine of the phase difference between the source voltage and the source fundamental current. With an increasing firing angle, the phase difference decreases resulting in an improved displacement factor, Fig. 4.10 shows the displacement factor for different firing angles

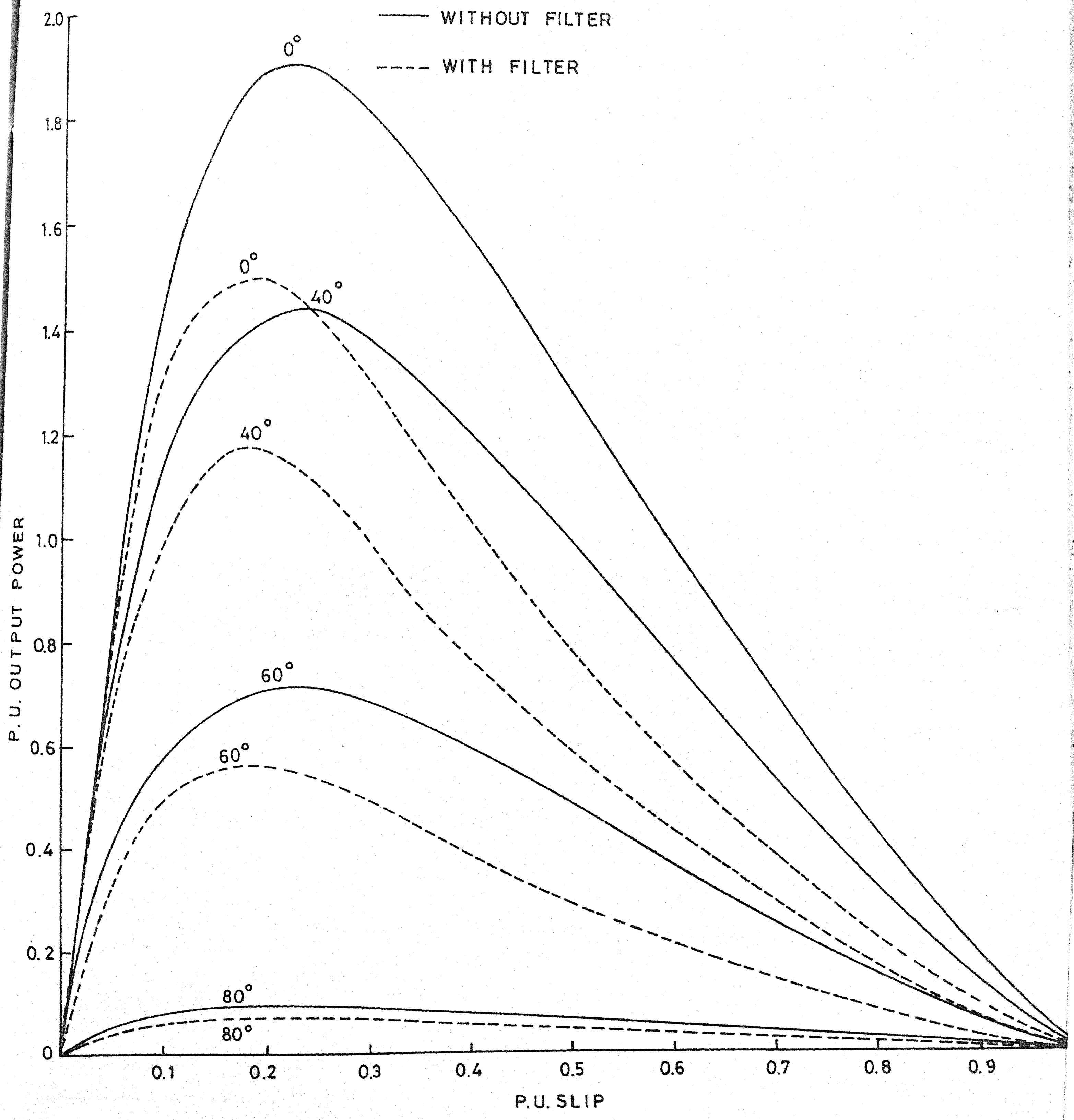


FIG. 4.8 MOTOR OUTPUT POWER VERSUS SLIP FOR DIFFERENT FIRING ANGLES.

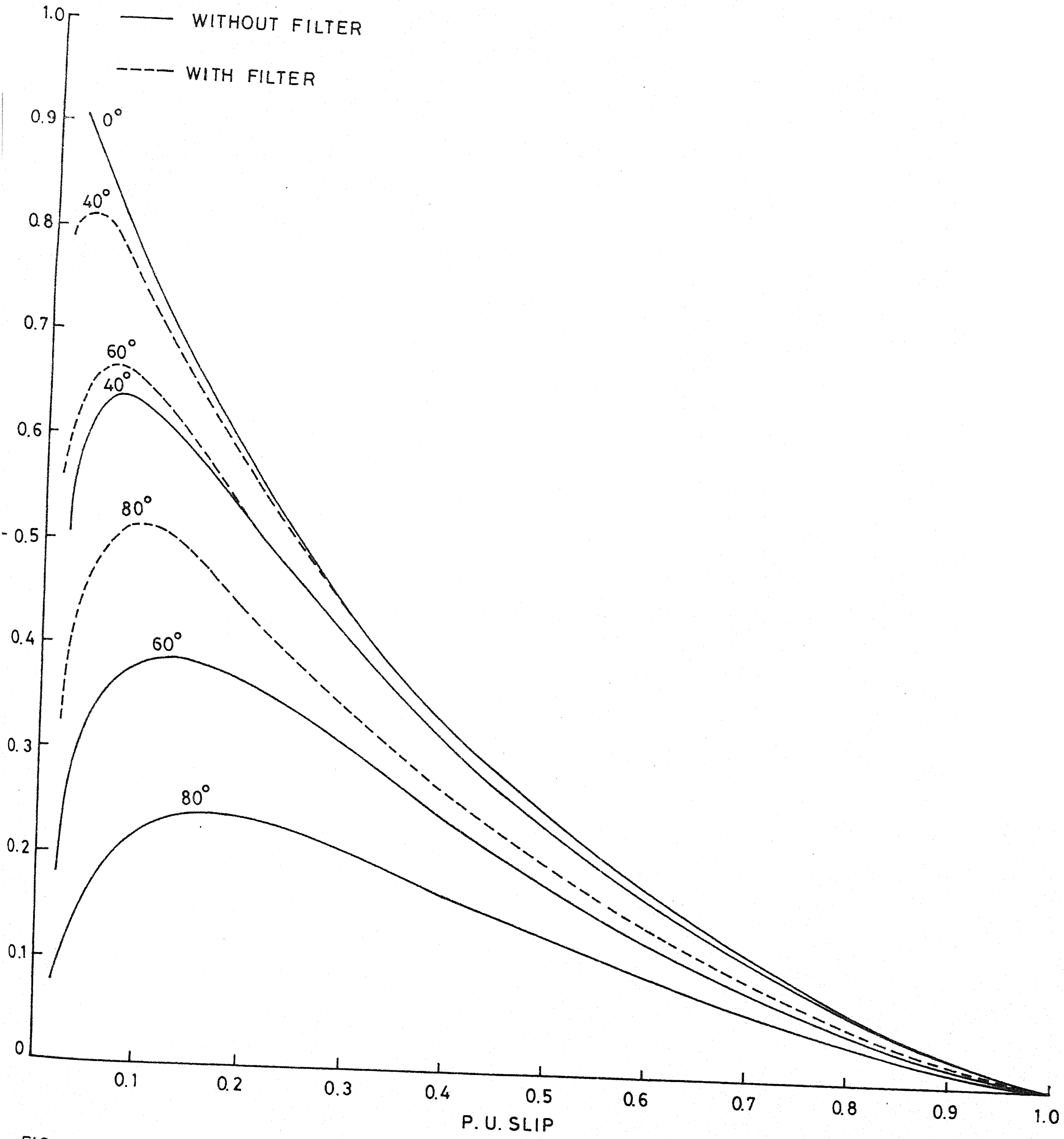


FIG. 4.9 MOTOR EFFICIENCY VERSUS SLIP FOR DIFFERENT FIRING ANGLES.

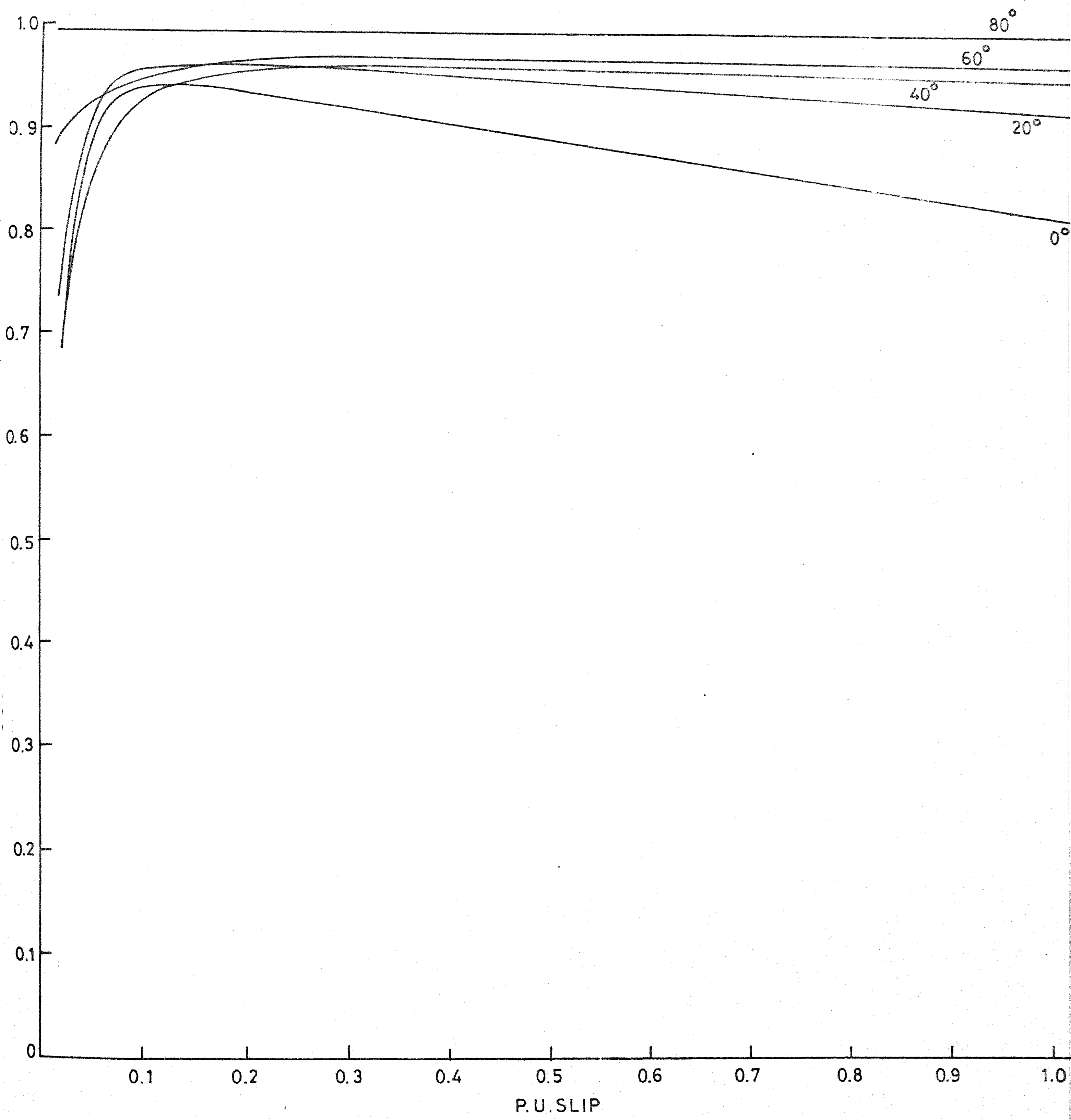


FIG. 4.10 SOURCE DISPLACEMENT FACTOR VERSUS SLIP FOR DIFFERENT FIRING ANGLES WITHOUT FILTER.

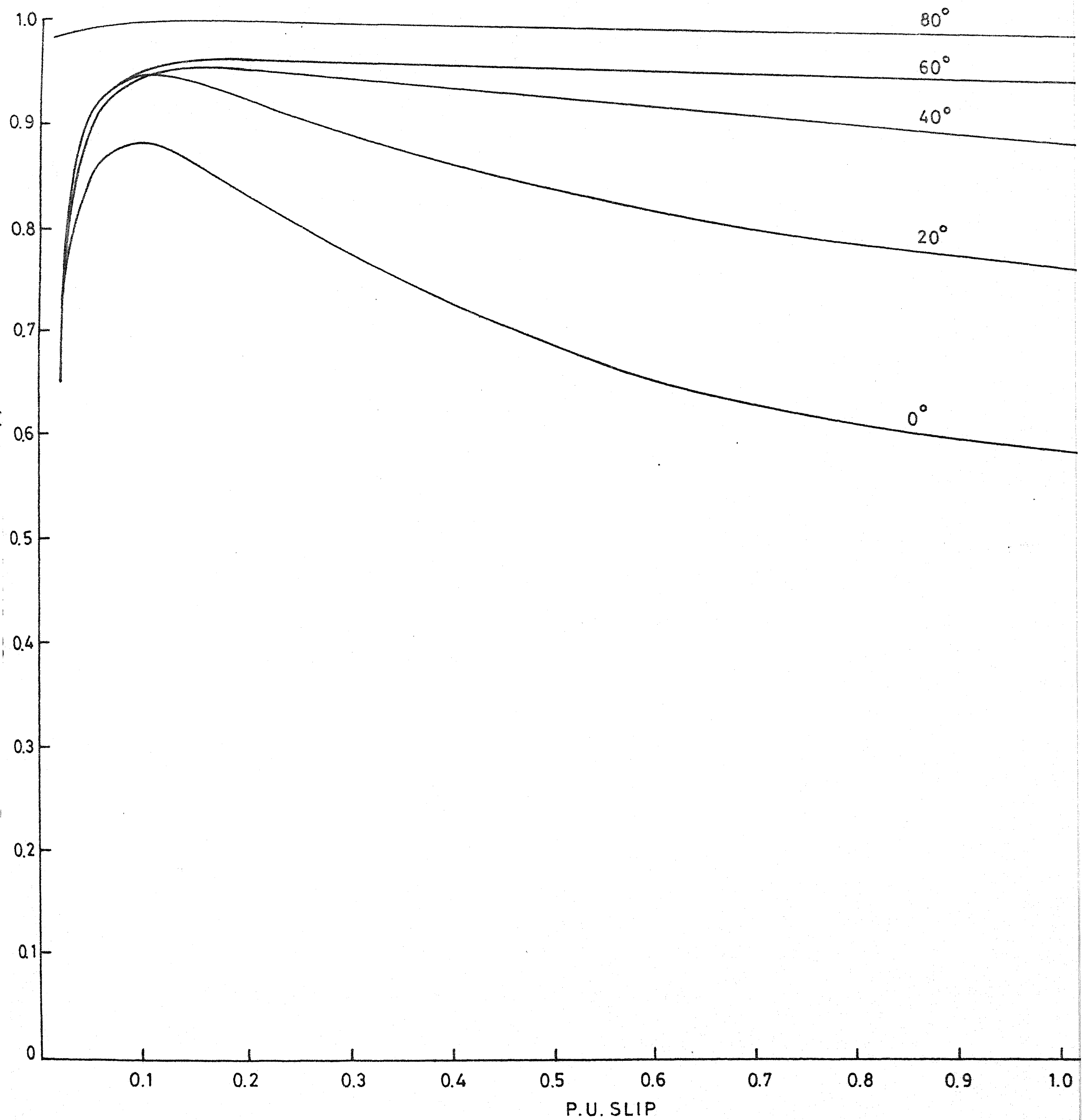


FIG. 4.11 SOURCE DISPLACEMENT FACTOR VERSUS SLIP FOR DIFFERENT FIRING ANGLES WITH FILTER.

for the motor without filter while Fig. 4.11 shows the same characteristic with filter. With a filter there is a slight reduction in the displacement factor for low firing angles, but for higher angles there is not much difference.

4.3.8 Source Power Factor

The source power factor depends on the displacement factor, fundamental component and harmonic content in the source current. At low firing angles, the harmonic content is low and the displacement factor is also close to unity. After a certain value of firing angle, the harmonic content becomes significant resulting in low power factor. At large firing angles, the harmonic content increases and the supply power factor deteriorates. Fig. 4.12 and 4.13 show the variation of power factor with slip for both with and without filter. An additional reactance results in a slight reduction in the source power factor.

4.3.9 comparison between theoretical and experimental results.

Fig. 4.14 shows the output power verses slip and source power factor verses slip characteristics. The torque-slip characteristic for the same firing angles are illustrated in

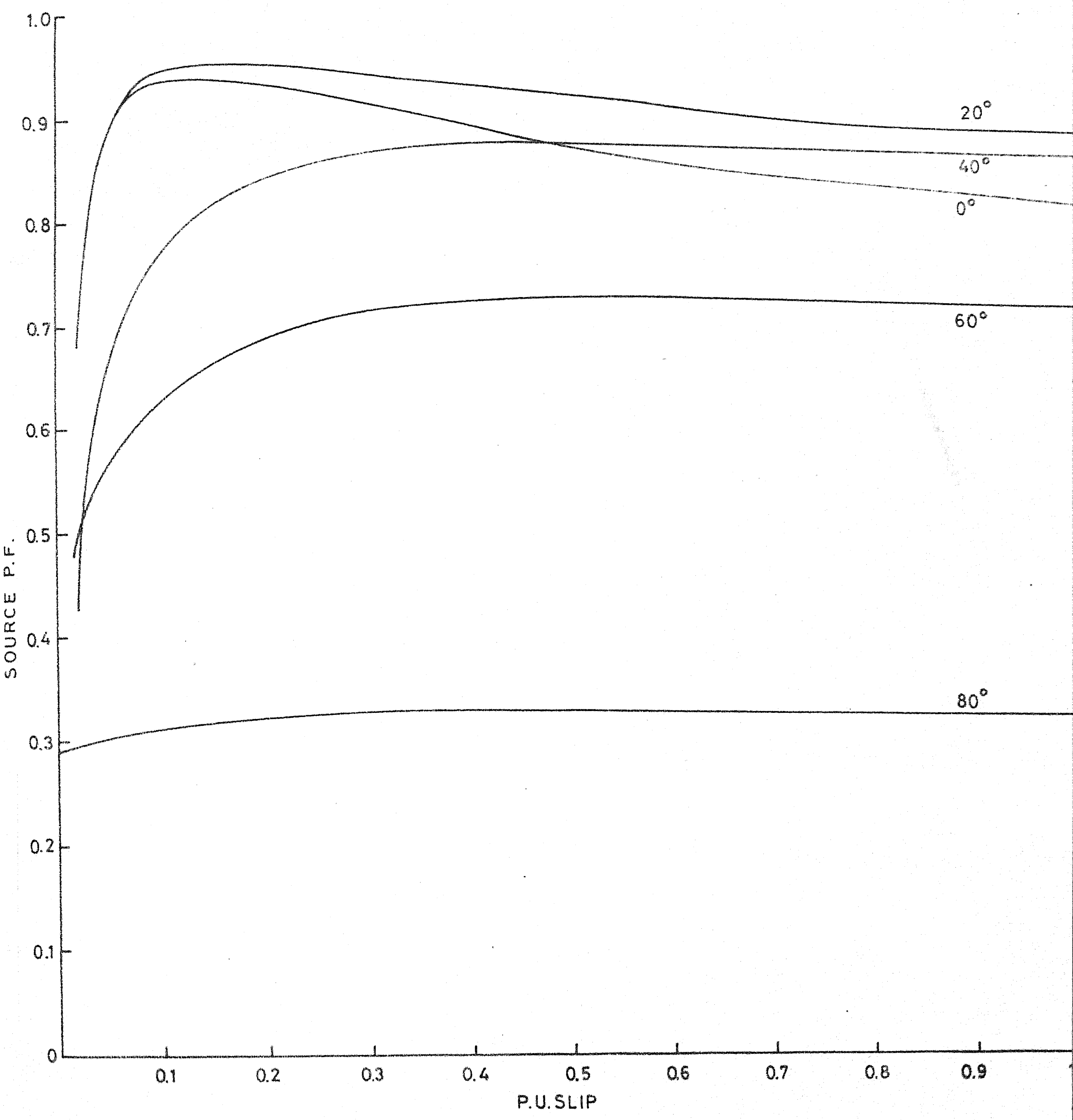


FIG. 4.12 SOURCE POWER FACTOR VERSUS SLIP FOR DIFFERENT FIRING ANGLES WITHOUT FILTER.

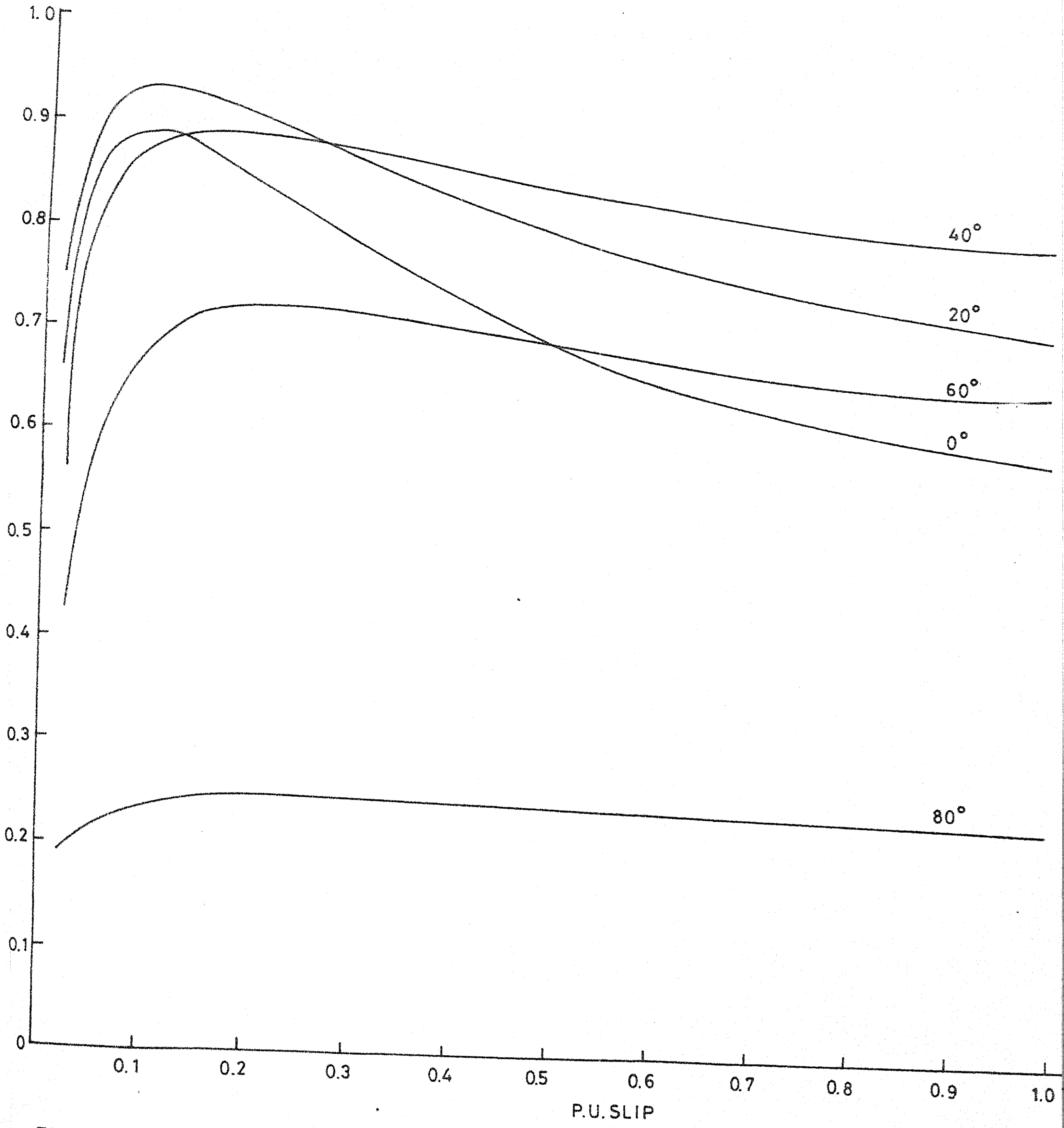
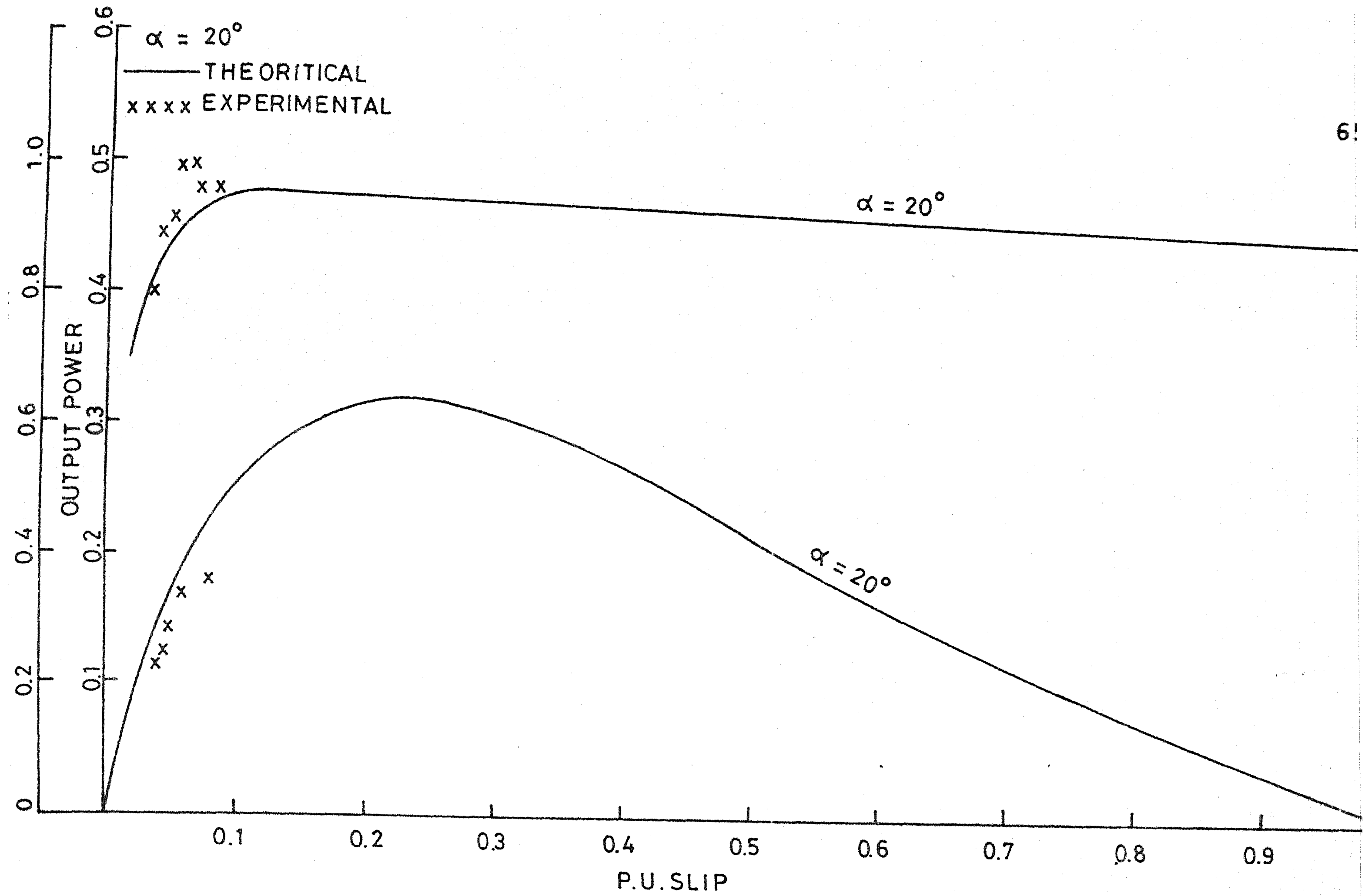
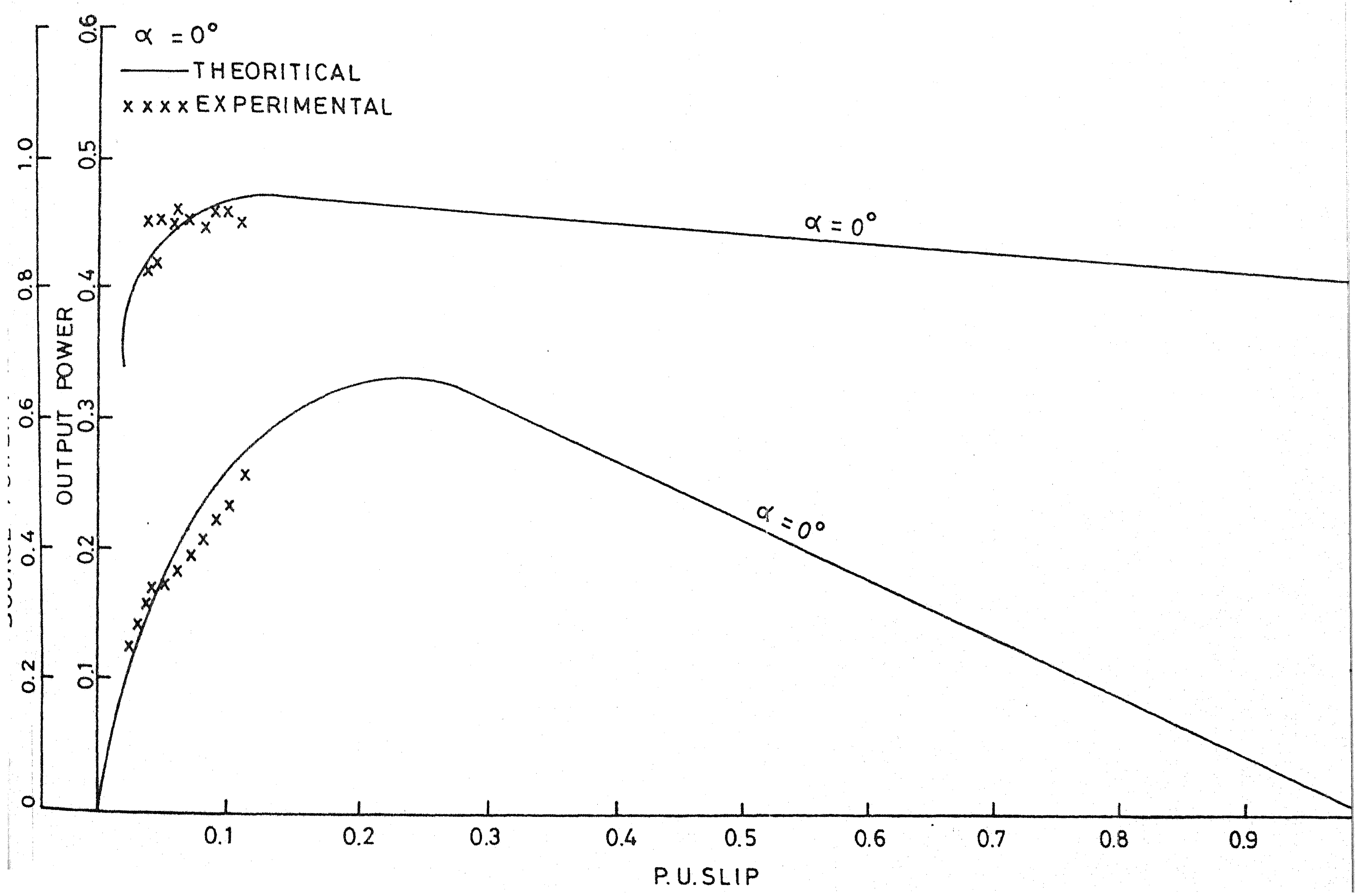


FIG. 4.13 SOURCE POWER FACTOR VERSUS SLIP FOR DIFFERENT FIRING ANGLES WITH FILT


α = 20°
THEORITICAL
xxxx EXPERIMENTAL
α = 20°
α = 20°
OUTPUT POWER
P.U. SLIP
0
0.2
0.4
0.6
0.8
1.0
0.1
0.2
0.3
0.4
0.5
0.6
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9


α = 0°
THEORITICAL
xxxx EXPERIMENTAL
α = 0°
α = 0°
OUTPUT POWER
P.U. SLIP
0
0.2
0.4
0.6
0.8
1.0
0.1
0.2
0.3
0.4
0.5
0.6
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9

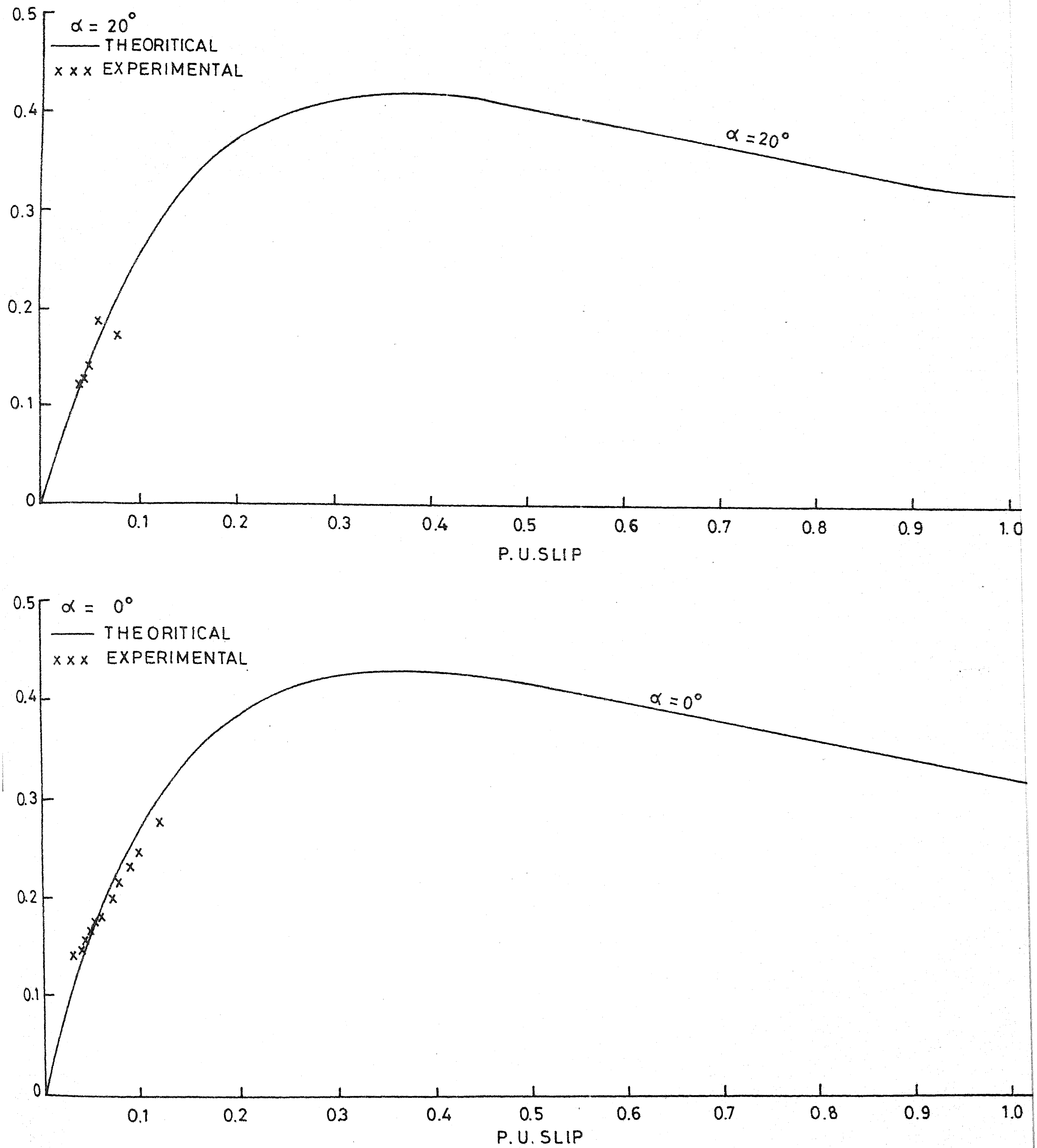


FIG. 4.15 TORQUE VERSUS SLIP.

Fig. 4.15. Solid lines show the theoritical and experimental points are also indicated in all these figures.

These results are taken at 100 volts supply.

It may be noted that there is a satisfactory agreement between simulation and experimental results.

Fig. 4.16 shows input voltage, output voltage and the motor current waveforms.

Fig. 4.17 shows the source current waveform.

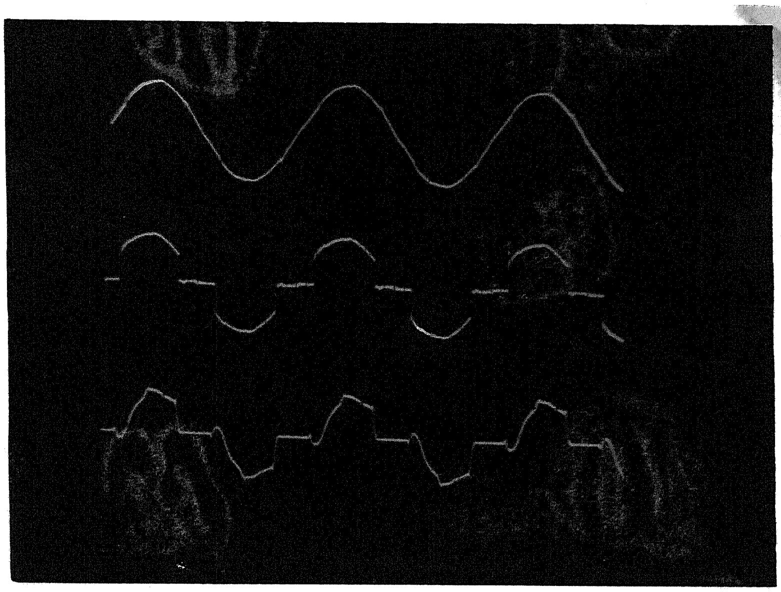


Fig. 4.17 Oscillogram showing input voltage, output voltage and input current

CHAPTER 5

CONCLUSION AND SCOPE FOR FUTURE WORK

The results discussed in the last chapter clearly indicate the superiority of the symmetrical voltage controller over the commonly used phase angle controller particularly for the passive load. Some application where this type of AC chopper can satisfactorily be used is a heating load such as heater, furnace and oven etc. The harmonics generated in the output current will not have any adverse effect on the load. The power supplied to the load and the source power factor are improved with the symmetrical voltage controller if compared with the phase angle controller.

The draw back which is common to both the controllers is that at low voltages the harmonics in the source current cause distortion in the source voltage. If the source current is high enough, then the distortion of the source voltage results in considerable additional loss to loads connected to the same source. The distortion is mainly due to low frequency harmonics. This can be eliminated by using multipulse width modulation technique instead of single pulse modulation. This will result in high frequency distortion of the source voltage. However this high frequency distortion can be easily eliminated

by using small-sized filters. Then the loss in the load will be less. This is the feature which is not present in case of the phase angle controller. The other advantage with multi-pulse width modulation is that the power factor is likely to be better than with single pulse chopper because of elimination of low frequency harmonics and reduced high frequency harmonics due to easy filtering.

Though there is a significant improvement in the source power factor but the third harmonic in the rotor circuit results in poor efficiency in case of the active load (Three phase induction motor).

The addition of a filter in the stator circuit improves efficiency but it results in slight reduction in power factor and considerable reduction in the torque at low speeds. Therefore the application is limited to the type of loads, which has the parabolic characteristic (Torque is proportional to the square of the speed) and very low starting torque.

With multipulse width modulation technique the harmonic content can be reduced considerably and additional filter may not be required. It may be interesting to investigate with multi-pulse width modulation, and the optimum number of pulses may be determined.

REFERENCES AND BIBLIOGRAPHY

1. D.A. Paice, 'Induction motor speed control by stator voltage control,' IEEE Trans. Power App. Syst., Vol. PAS-87, No.2, pp. 585-590, Feb. 1968.

2. S.R. Doradla, C. Nagmani, and Subhankar Sanyal, 'A sinusoidal pulsewidth modulated three-phase ac to dc converter-fed dc motor drive,' in Conf. Rec. 1984, 19th Annual Meet. IEEE Ind. Appl. SOC., pp. 668-679.

3. Alexander Mozdzer, Jr., Bimal K. Bose, 'Three-phase ac power control using power transistors,' IEEE Trans. Ind. Appl., Vol. IA-12, No.5, pp. 499-505, Sep./Oct. 1976.

4. Gilles Roy, Pierre Poitevin, and Guy Oliver, 'A comparative study of single-phase modulated ac choppers,' IEEE Trans. Ind. Appl., Vol. IA-20, No.6, pp. 1498-1506, Nov./Dec. 1984.

5. L.J. Jacovides, 'Analysis of induction motor drives with nonsinusoidal supply voltage under harmonic analysis,' IEEE Trans. Ind. Appl., Vol. IA-9, No.6, pp. 741-747, Nov./Dec. 1973.

6. J.M.D. Murphy, 'Thyristor control of ac motors,' Pergamon Press, Oxford, 1973.

7. R.S. Ramshaw, 'Power electronics - thyristor controlled power for electric motors,' Chapman and Hall, London, 1979.

8. M.G. Say, 'Alternating current machines,' Pitman Publishing, Bath, 1978.

9. M. Ramamoorty, 'Thyristor and their applications,' East West Press, 1977.

10. G.C. Jain, 'The effect of voltage waveform on the performance of the three-phase induction motor,' IEEE Trans. Power App. Syst., Vol. PAS-83, pp. 561-566, June 1964.

11. M. Arunachalam, 'Solid state speed control of induction motors,' Ph.D. Thesis, I.I.T., Kanpur 1977.

APPENDIX I

SPECIFICATIONS OF INDUCTION MOTOR

Rated voltage	=	415V
Rated current	=	3.2A
Rated output	=	1.5 H.P.
Rated Speed	=	2840 rpm
Connection	=	Y
Stator resistance	=	6.8 ohms
Stator reactance	=	3.9 ohms
Rotor resistance	=	4.72 ohms
Rotor reactance	=	3.9 ohms
Magnetising reactance	=	182.724 ohms

APPENDIX II

SPECIFICATIONS OF MJ 10009

V_{CEO}	=	500V
V_{CEV}	=	700V
I_C (PEAK)	=	30A
I_C (continuous)	=	10A
h_{FE}	=	30/300
t_s (max)	=	2 μsec
t_f (max)	=	0.6 μsec
P_D (case)	=	175 watts